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Looking for charged (meta)stable particles in MoEDAL-MAPP

Vasiliki A. Mitsou

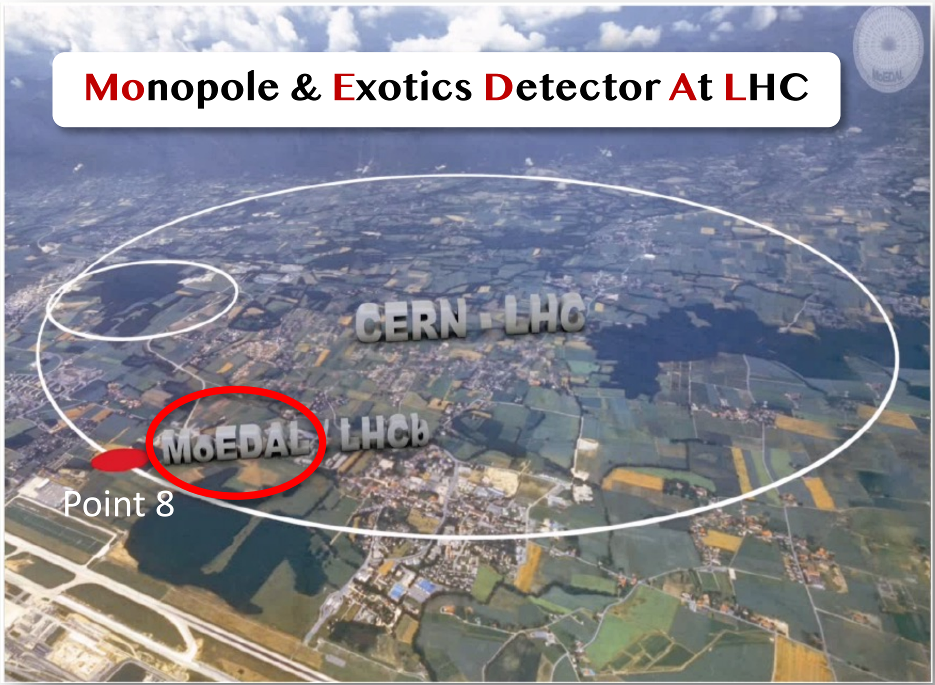
for the MoEDAL Collaboration

MoEDAL

Workshop on Multi-front Exotic phenomena in Particle and Astrophysics (MEPA 2022)

16-19 December 2022
Hefei
University of Science and Technology of China

MoEDAL Collaboration



~70 physicists from 21 institutions

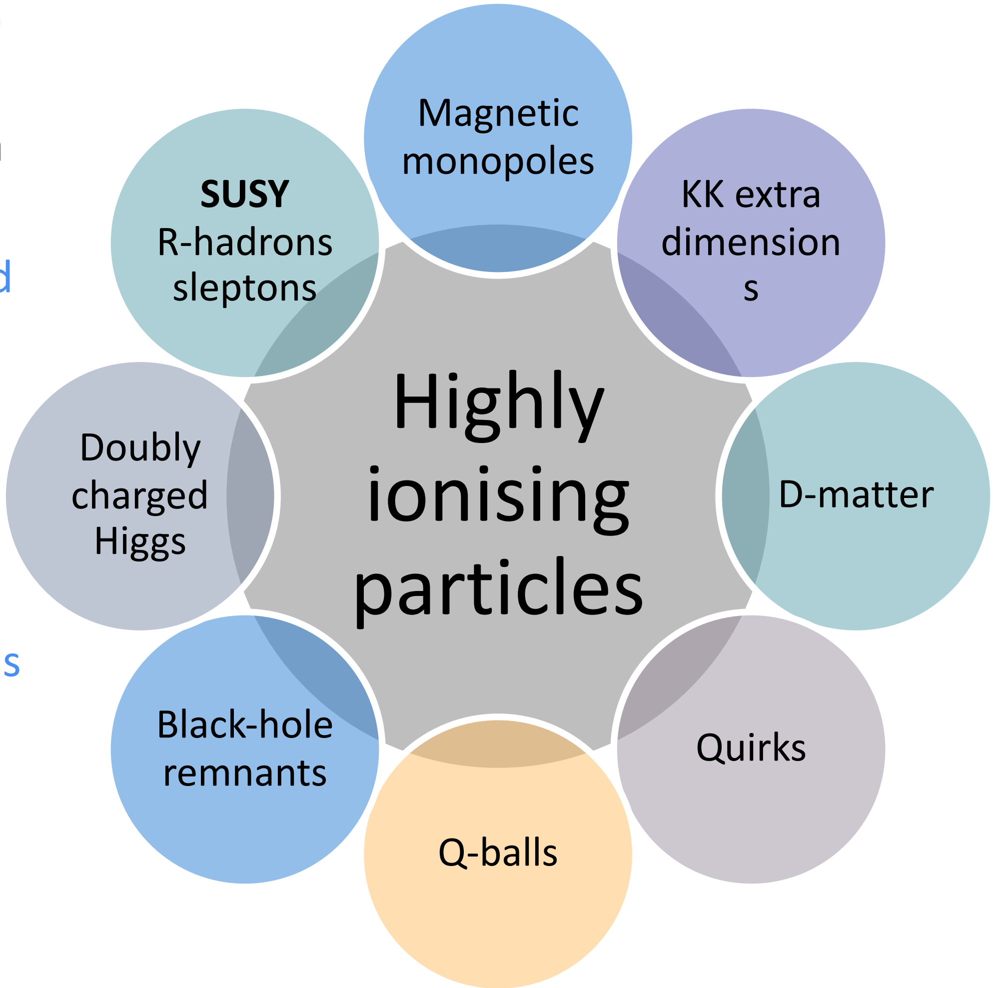
UNIVERSITY OF ALABAMA
UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
HELSINKI INSTITUTE OF PHYSICS
UNIVERSITY OF MONTREAL
CERN
CONCORDIA UNIVERSITY
IMPERIAL COLLEGE LONDON
KING'S COLLEGE LONDON
NATIONAL INSTITUTE OF TECHNOLOGY, KURUKSETRA
TECHNICAL UNIVERSITY IN PRAGUE
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

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

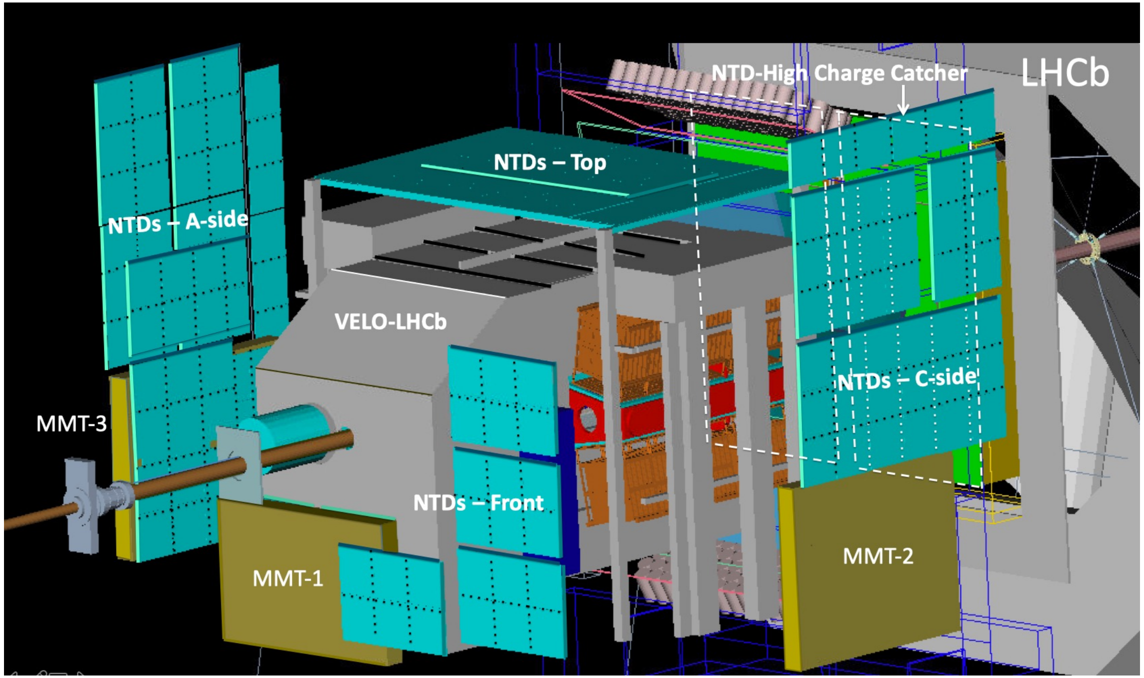
MoEDAL physics goals

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

Baseline MoEDAL detector



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

THREE DETECTOR TECHNOLOGIES

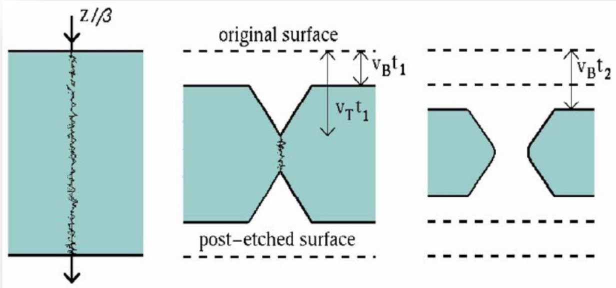
① Nuclear Track Detectors
- **Low-threshold NTD** array
  $z/\beta > \sim 5\text{-}10$
- High Charge Catcher NTD (**HCC-NTD**) array
  $z/\beta > \sim 50$

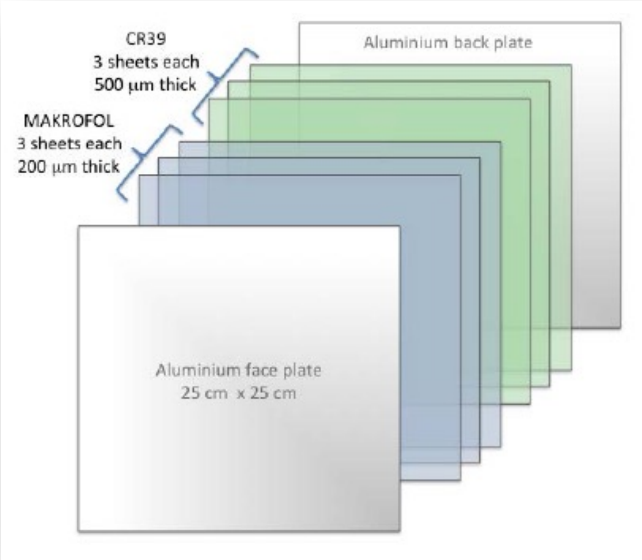
② Monopole Trapping detector (**MMT**) – aluminum bars

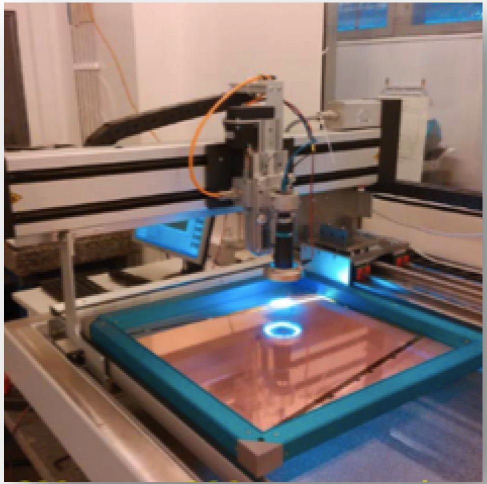
③ **TimePix** radiation background monitor

Nuclear Track Detectors (NTDs)

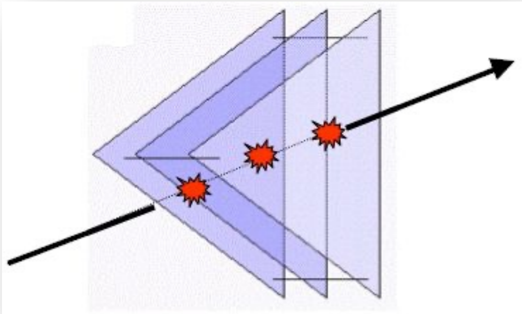
- Passage of a highly ionising particle through the plastic NTD marked by an *invisible* damage zone (**"latent track"**) along the trajectory
- Damage zone revealed as a **cone-shaped etch-pit** when the plastic sheet is **chemically etched**
- Plastic sheets are later **scanned** to detect etch-pits





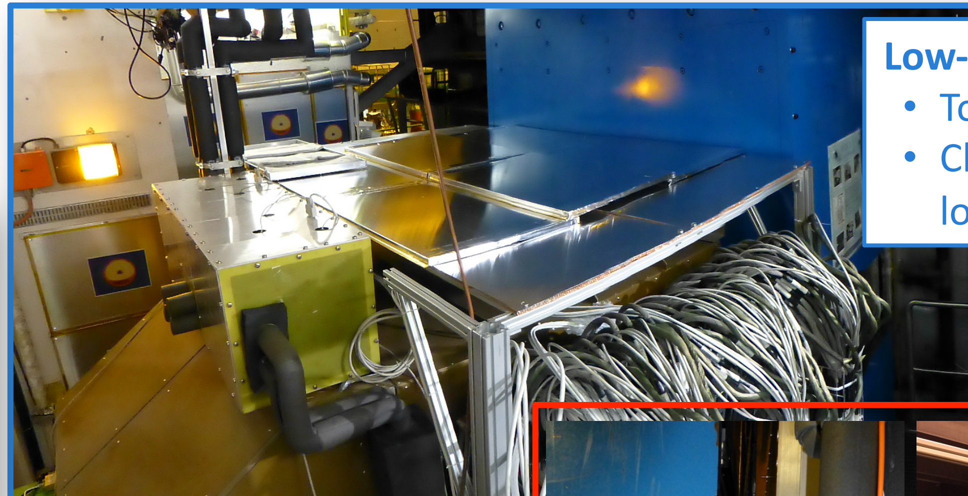


Looking for aligned etch pits in multiple sheets



Run-2 NTD deployment

Low-threshold NTD
NTDs sheets kept in boxes mounted onto cavern walls



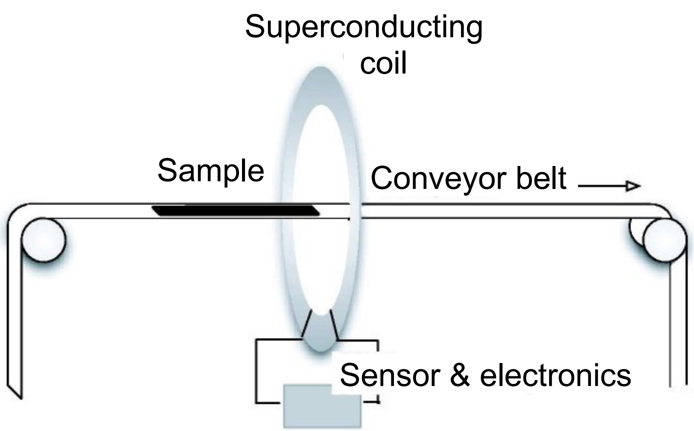
Low-threshold NTD
- Top of VELO cover
- Closest possible location to IP

HCC-NTD
Installed in LHCb acceptance between RICH1 and Trigger Tracker

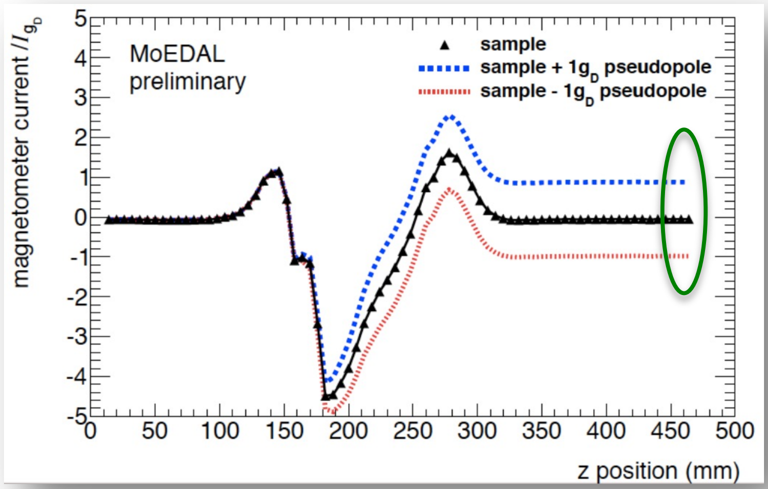
Monopole binding & SQUID analysis

- Monopoles can bind to nuclei and get trapped
- Exposed material scanned in superconducting quantum interference device (SQUID)
- **Persistent current:** difference between resulting current after and before
  - non-zero persistent current
    ⇒ isolated magnetic charge in sample

See, e.g. de Roeck et al, EPJC 72 (2012) 2212



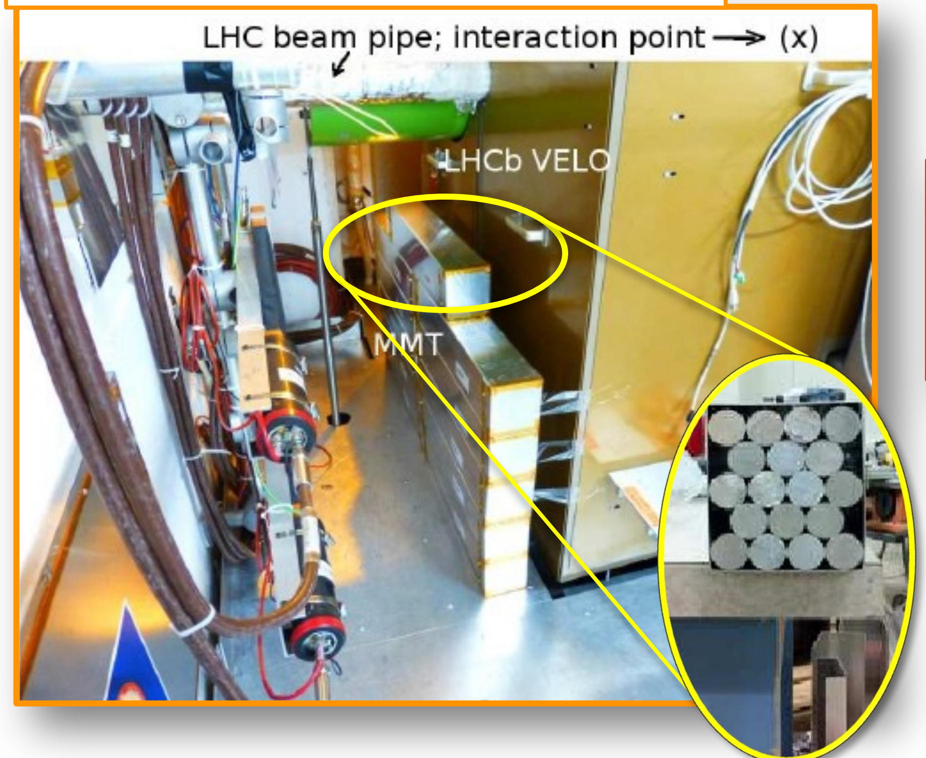
Calibration
Typical sample & pseudo-monopole curves



MMTs deployment

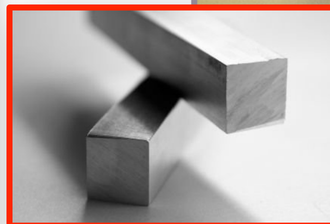
2012

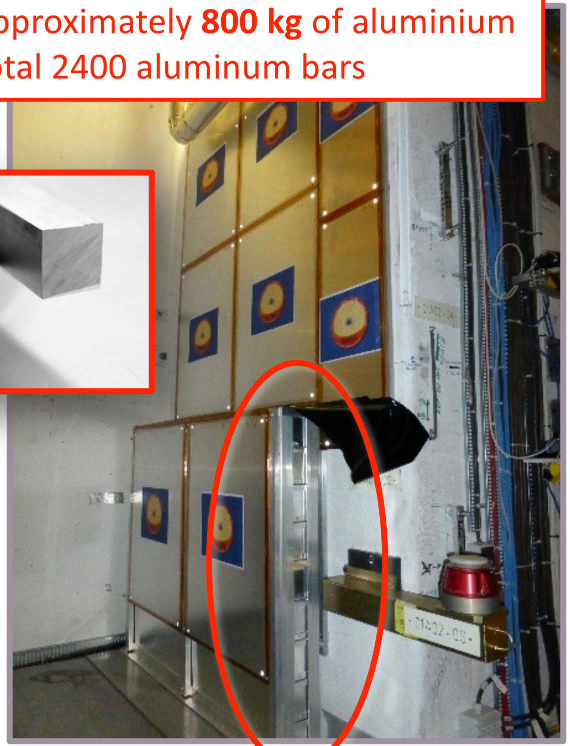
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (**160 kg**)



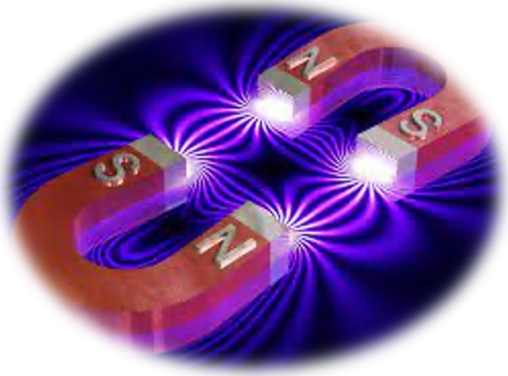
2015-2018

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





Magnetic monopole searches



Paul Nylander, burgman123.com

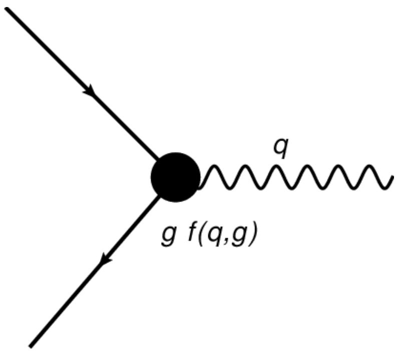
Symmetrising Maxwell

- As no magnetic monopole had ever been seen, Maxwell kept isolated magnetic charges out from his equations – making them *asymmetric*
- A magnetic monopole restores the symmetry to Maxwell's equations

Laws	Without monopoles	With magnetic monopoles
Gauss's law	$\nabla \cdot \mathbf{E} = 4\pi\rho_e$	$\nabla \cdot \mathbf{E} = 4\pi\rho_e$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B} = 4\pi\rho_m$
Faraday's law	$-\nabla\times\mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}$	$-\nabla\times\mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} + 4\pi\mathbf{J}_m$
Ampère's law	$\nabla\times\mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$	$\nabla\times\mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$

- Symmetrised Maxwell's equations invariant under rotations in (**E**, **B**) plane of the electric and magnetic field
- Duality ➤ no fundamental distinction between electric and magnetic charge

Monopole properties in a nutshell



- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges integer multiples of g_D: $g = ng_D$, $n = 1, 2, \ldots$
- Photon-monopole coupling constant
  - large: $g/\hbar c \sim 20$ (precise value depends on units)
  - following duality arguments, may be β-dependent, $\beta = \sqrt{1 - \frac{4M^2}{s}}$
- Monopoles would *accelerate* along field lines – and *not curve* as electrical charges in a magnetic field

$$\vec{F} = g\left(\vec{B} - \vec{v} \times \vec{E}\right)$$

- Dirac monopole is a point-like particle; GUT monopoles are extended objects
- Monopole spin and mass not determined by theory → free parameters
- Monopole interaction with matter: high ionisation, Cherenkov radiation, multiple scattering

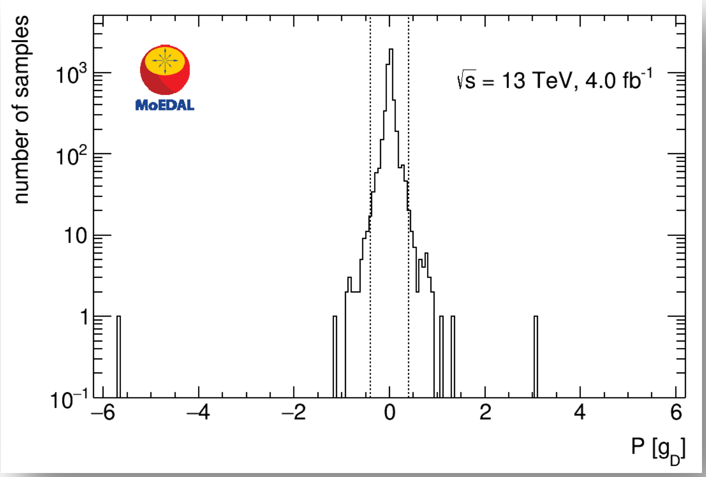
For a review on monopole theory and searches, see: Mavromatos & VAM, Int.J.Mod.Phys.A 35 (2020) 2030012

MMT scanning results

- MMTs scanned through the SQUID at the *ETH Zurich Laboratory for Natural Magnetism*
- MMT bars are cut into pieces and fed into the SQUID two or more times, depending on scanning campaign
- Instabilities can be caused by several known instrumental and environmental factors
  - spurious flux jumps when the slew rate is increased
  - noise currents in the SQUID feedback loop
  - physical vibrations and shocks
  - variations in external magnetic fields
  - …
- Outliers are **scanned several times** further

No isolated magnetic charges found in MMT analyses

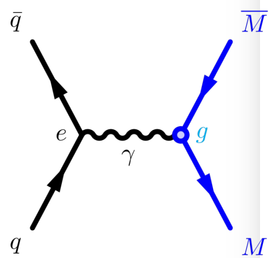
SQUID analysis – Persistent current after first two passages for all samples

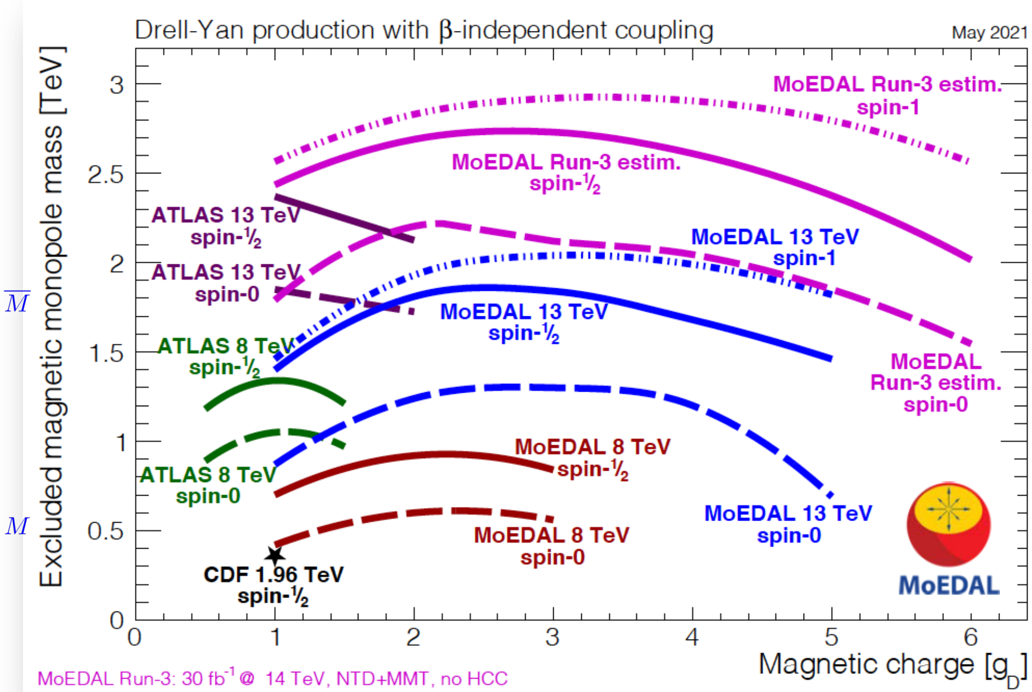


MoEDAL, PRL 123 (2019) 021802

Magnetic monopole limits

- Novelties in monopole models in MoEDAL considered w.r.t. other experiments
  - β-dependent coupling
  - spin-1 monopoles
  - γγ fusión
- More results expected in **Run-3** and **HL-LHC**



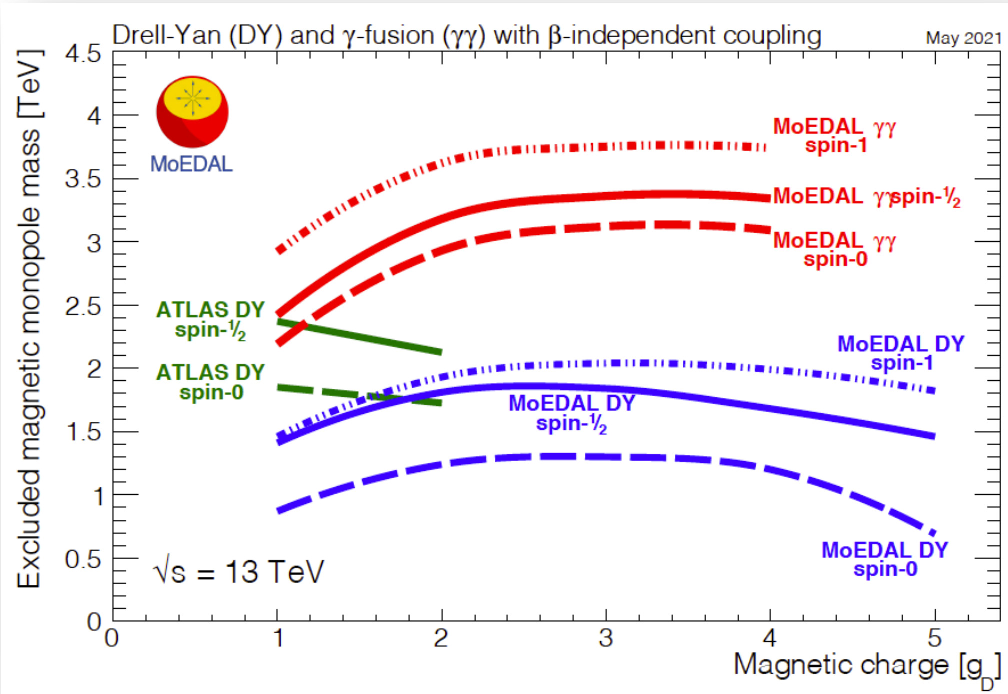


MoEDAL has set the world-best collider limits for |g| > 2 g_D

Mass limits extracted with Feynman-*like* diagrams that ignore non-perturbativity of large monopole-photon coupling. They serve as benchmarks to facilitate comparisons.

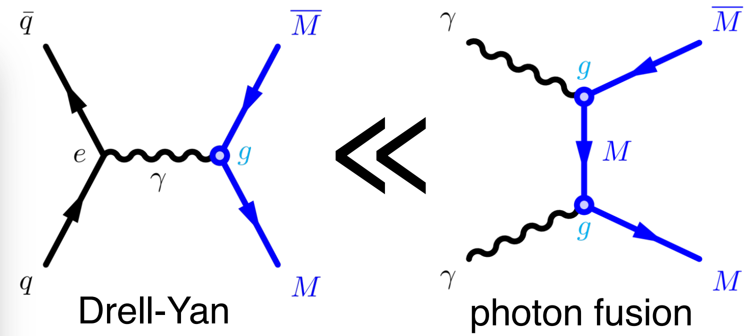
MoEDAL, JHEP 1608 (2016) 067, PRL 118 (2017) 061801, PLB 782 (2018) 510, PRL 123 (2019) 021802, PRL 126 (2021) 071801

Drell-Yan & γγ-fusion



MoEDAL, Phys.Rev.Lett. 123 (2019) 021802

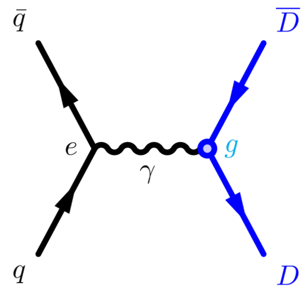
See also, Baines, Mavromatos, VAM, Pinfold, Santra, Eur.Phys.J.C 78 (2018) 966



Photon-fusion monopole production process has much higher cross section than Drell-Yan at LHC collision energies

Overall, MoEDAL achieved extended reach by combining Drell-Yan & γ-fusion production processes

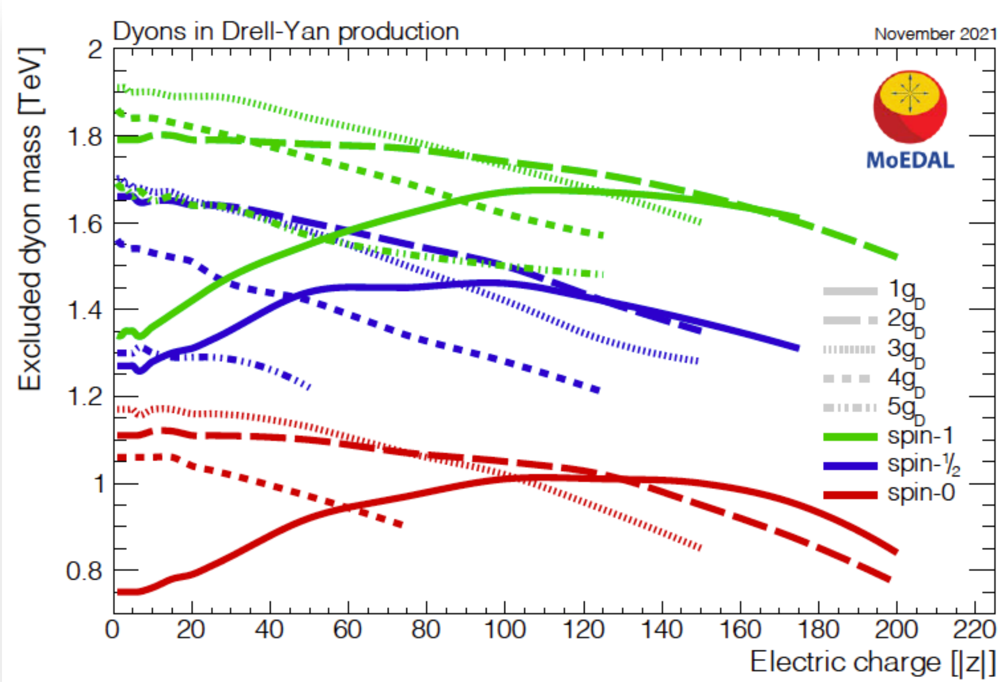
Dyons



- Dyons possess both electric and magnetic charge
- Excluded cross sections as low as **30 fb**
- Mass limits **750-1910 GeV** set by scanning MMTs for captured dyons

First explicit accelerator search for direct dyon production!

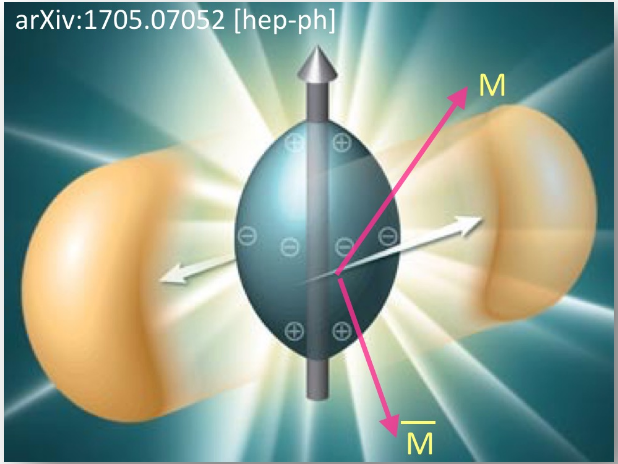
- Previous searches for highly ionising particles would, in principle, also have sensitivity to dyons
  - caution on behaviour under magnetic field

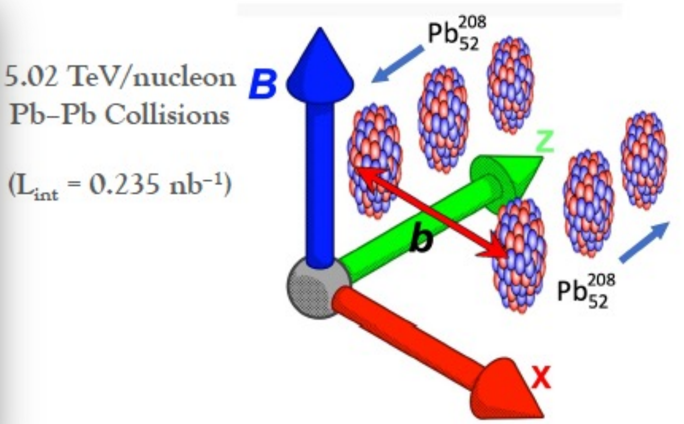


MoEDAL, [Phys.Rev.Lett. 126 (2021) 071801]

Monopoles via thermal Schwinger mechanism

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





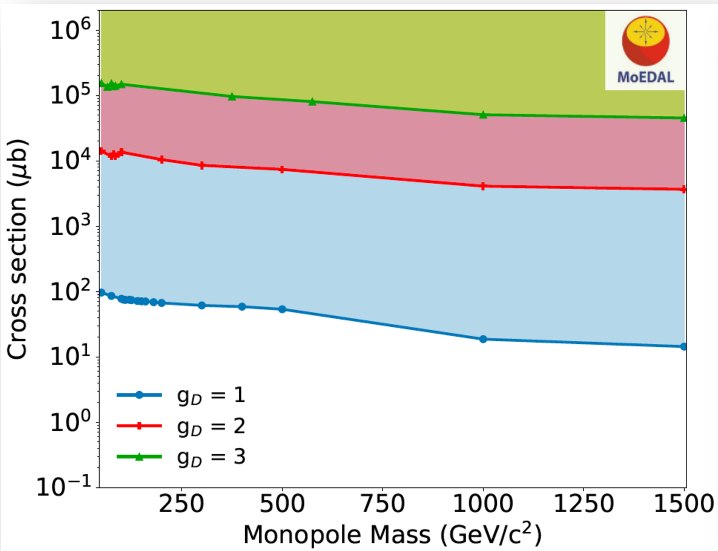
Advantages over DY & γγ-fusion production

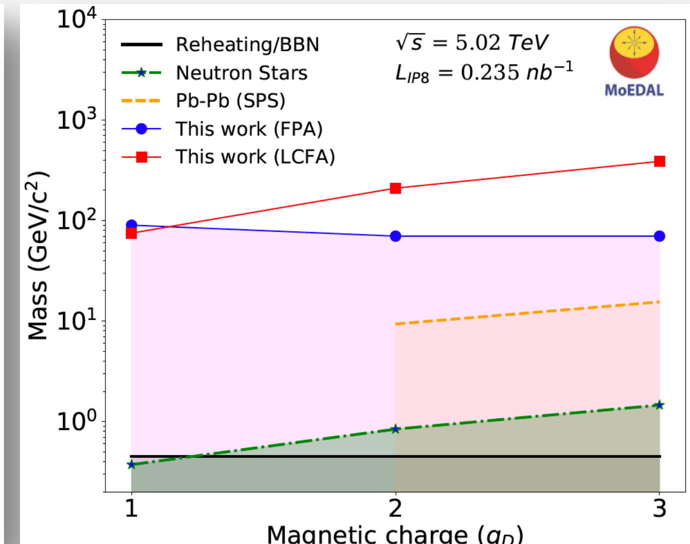
- cross-section calculation using semiclassical techniques ⇒ does not suffer from non-perturbative nature of coupling
- no exponential suppression $e^{-4/\alpha}$ for finite-sized monopoles

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

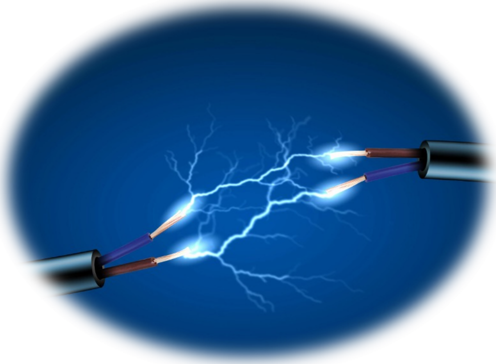




Monopole mass reach appears to be 20–30 times lower than current bounds from ATLAS and MoEDAL, however, this cross-section calculation is theoretically sound

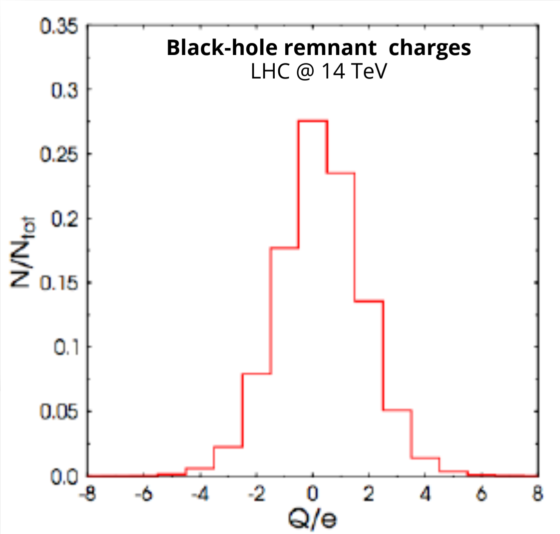
MoEDAL, Nature 602 (2022) 7895, 63-67

Electrically charged particles

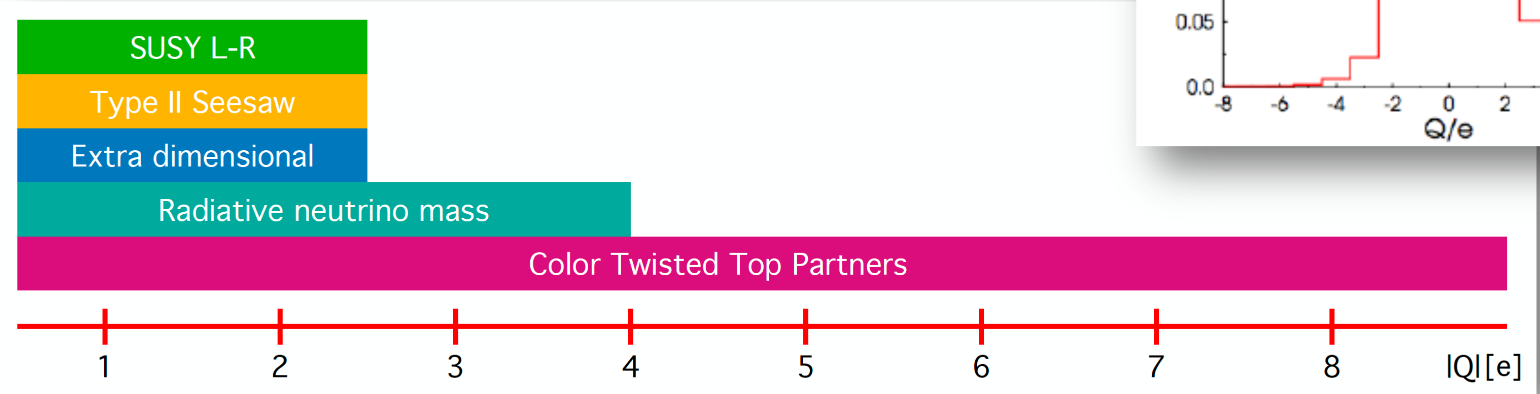

shutterstock.com

Multiply charged quasi-stable particles

- Highly Electrically Charged 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
- Detected by **high ionisation**



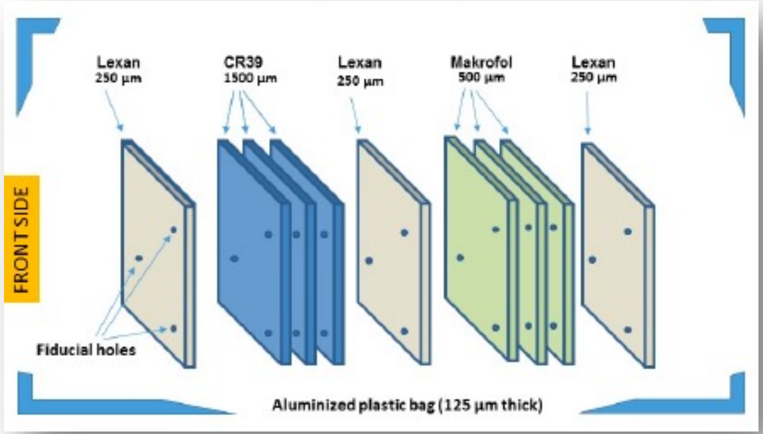
Hossenfelder, Koch, Bleicher, hep-ph/0507140

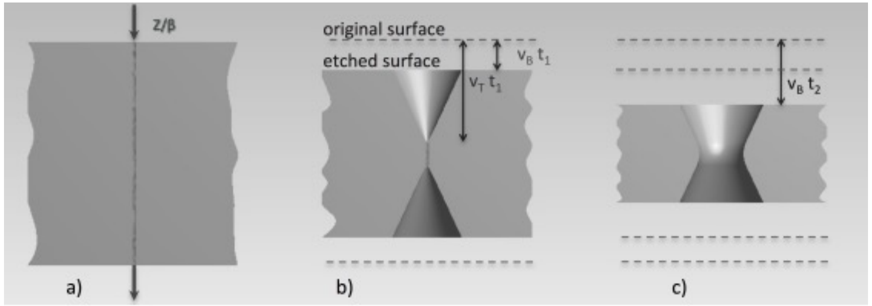


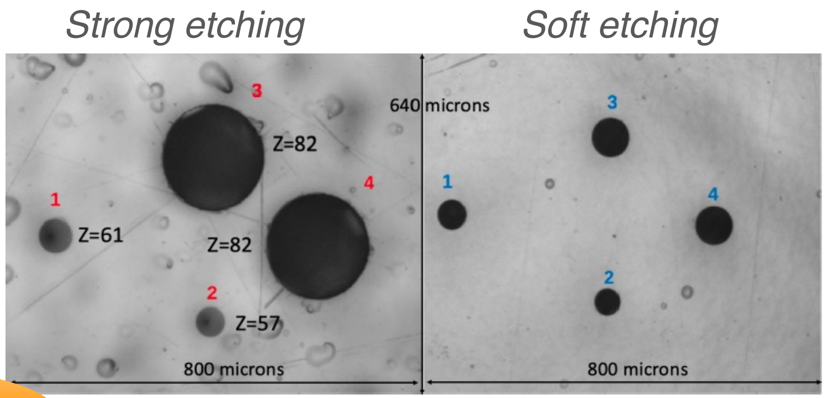
R. Masełek, DISCRETE2020-2021

NTD+MMT search for HECOs (and monopoles)

- **First NTD analysis for MoEDAL**
- Prototype NTD array of 125 stacks (7.8 m^2) exposed to 8 TeV *pp* collisions (Run 1)
- NTDs etched and scanned in INFN Bologna







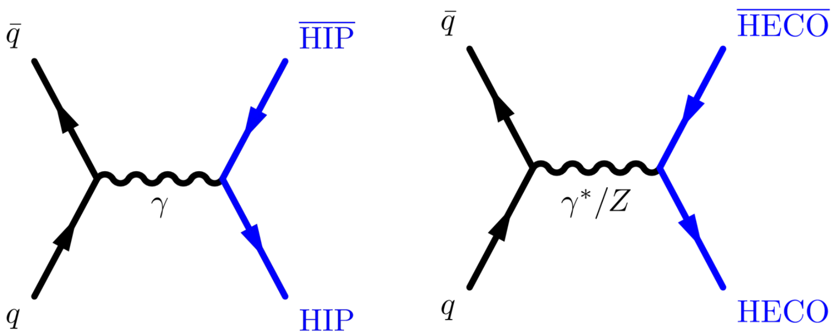
Calibration with 158 A GeV Pb^{82+} and 13 A GeV Xe^{54+} ion beams

No HIP candidates found in the NTDs stacks

MoEDAL, Eur.Phys.J.C 82 (2022) 694

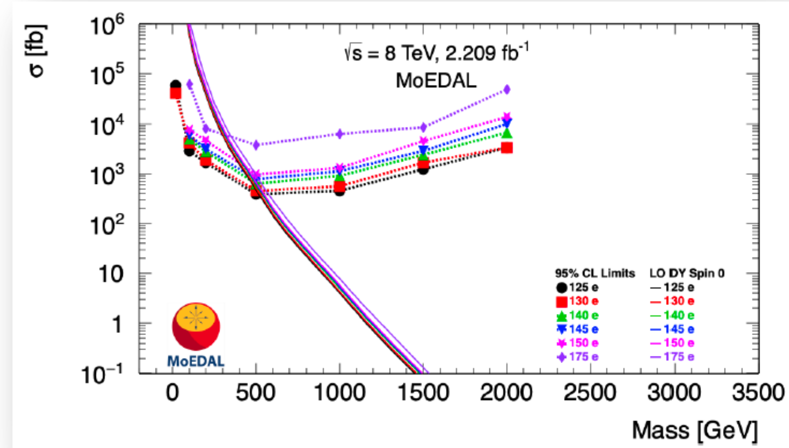
NTD results on HECOs

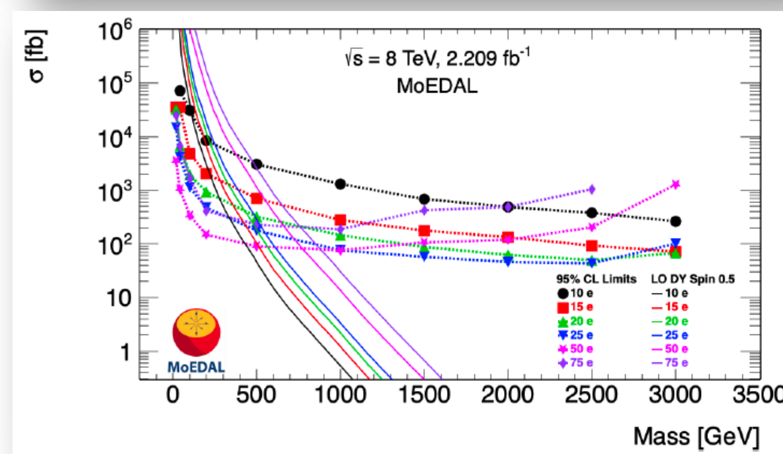
- Drell-Yan production
  - *Z* exchange is also taken into account for fermions [Song & Taylor, J.Phys.G 49 (2022) 045002]



  - non-perturbativity of large coupling can be tackled by appropriate **resummation** [Alexandre, Mavromatos, Musumeci, VAM, *in progress*]
- Limits set on HECO pair production with cross section **~ 30 – 70 pb**

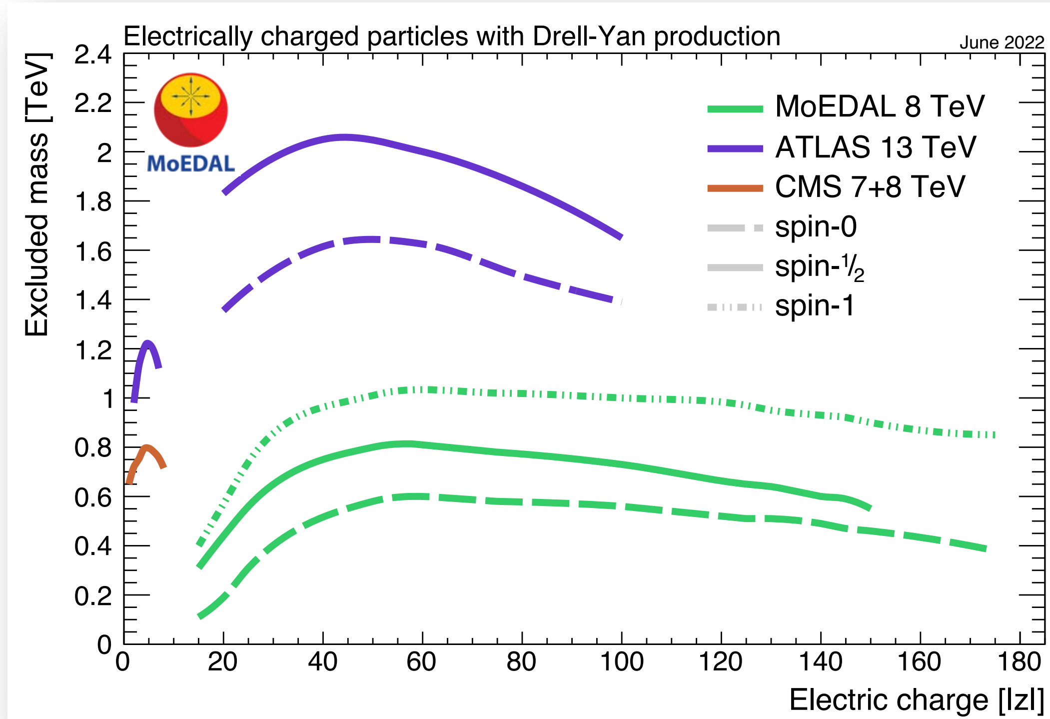
MoEDAL, EPJC 82 (2022) 694





HECOs summary

- MoEDAL set limits on HECOs with electric charges in the range **15*e* – 175*e*** and masses from **110 – 1020 GeV**
- Better sensitivity expected in ongoing **Run 2 analysis**
  - higher c.m.s. energy: 13 TeV
  - larger integrated luminosity
  - larger exposed NTD surface
  - lower CR39 *Z/β* threshold (5) than Macrofol (50)

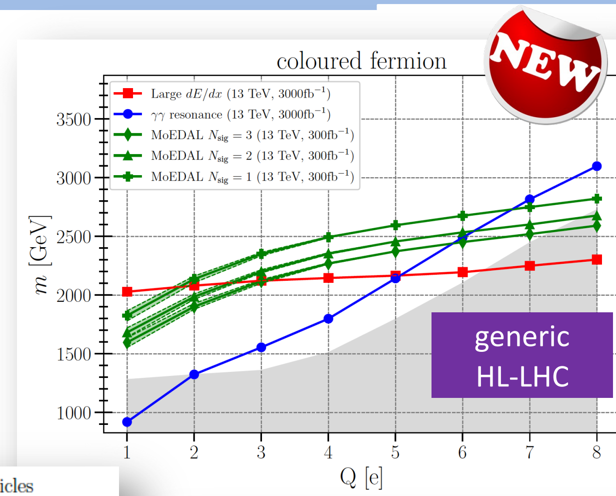


Only published ATLAS/CMS results shown

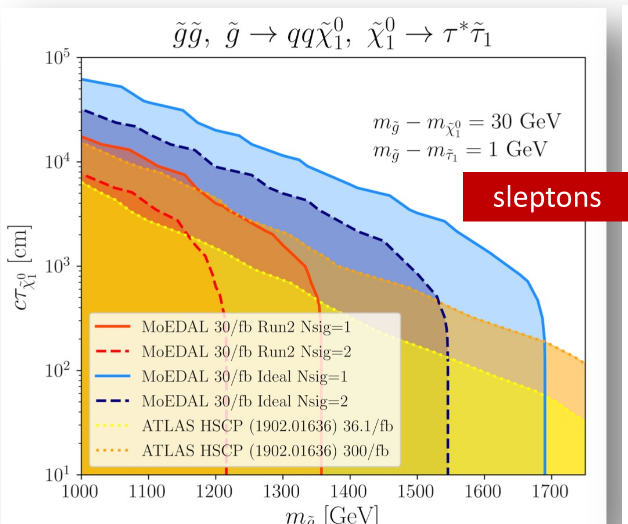
MoEDAL HECOs limits are the strongest to date, in terms of charge, at any collider experiment

"Low" electric charges

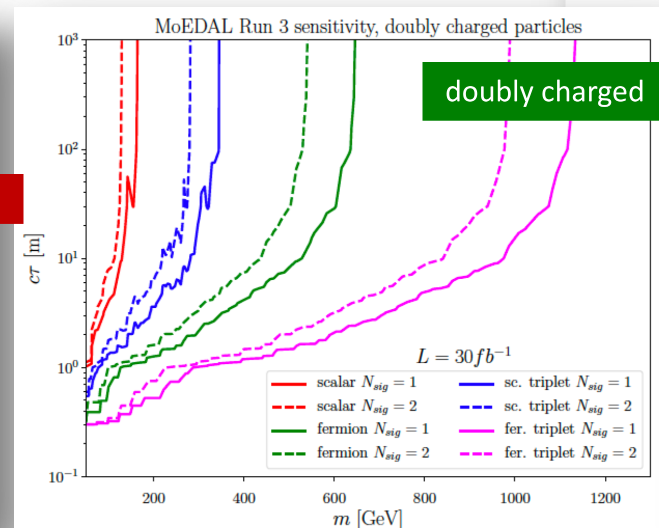
- Supersymmetry singly charged LLPs: sleptons, R-hadrons, charginos
- Doubly charged Higgs bosons and fermions
- Several models of ν masses → 2-, 3-, 4-ply charged
- **Generic multiply charged particles**



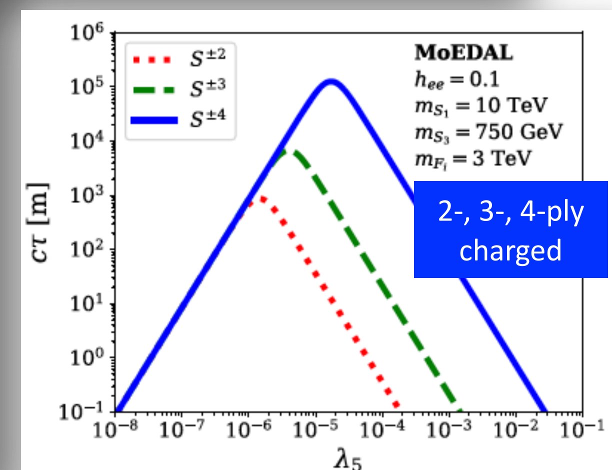
Altakach, Lamba, Masełek, VAM, Sakurai, EPJC 82 (2022) 848



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

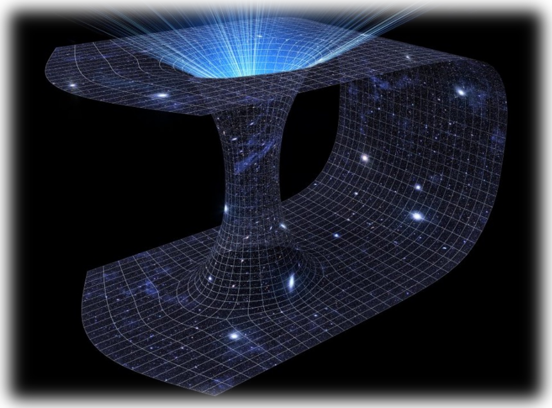


Acharya et al, EPJC 80 (2020) 572



Hirsch et al, EPJC 81 (2021) 697

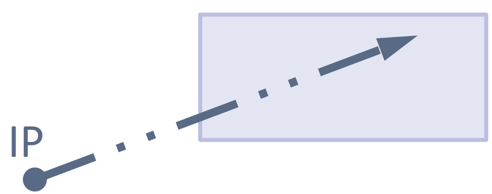
MAPP – Sensitivity to portal models



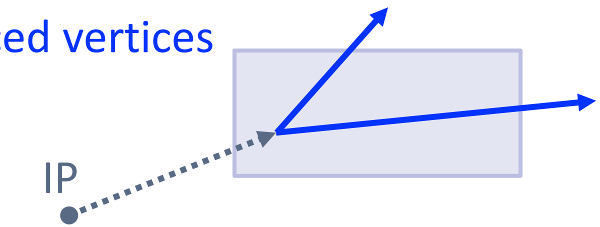
Credit: General Electric

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



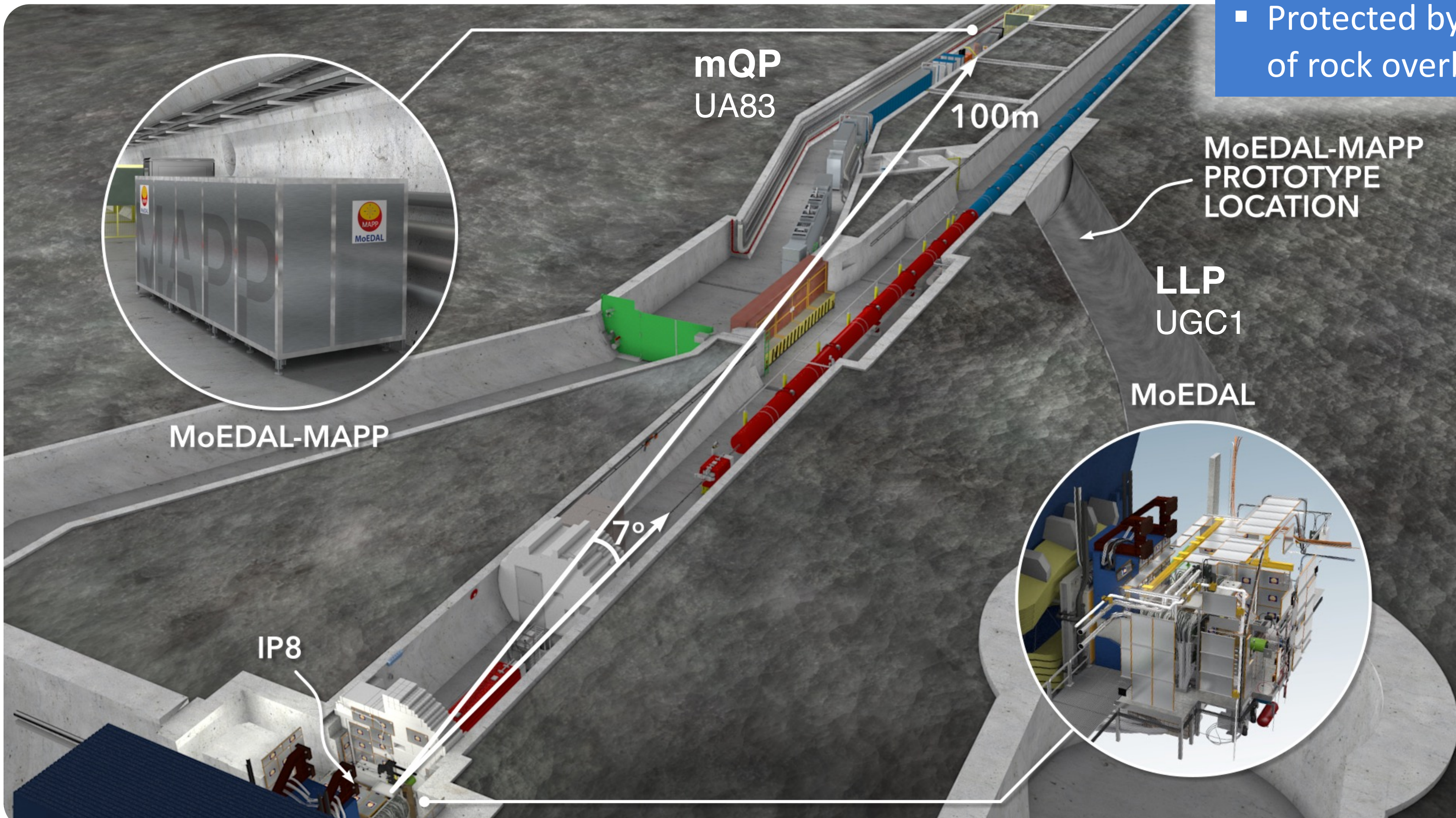
- Phase-1 ***approved*** *by CERN Research Board* on Dec 1st 2021
- **Phase-1** for **Run-3** (2022–2025): **MAPP-mQP** installation in UA83 is underway
  - start taking data in 2023
- **Phase-2 HL-LHC** (2029 –): Reinstall Phase-1 in UA83 and add **MAPP-LLP** in UGC1

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

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

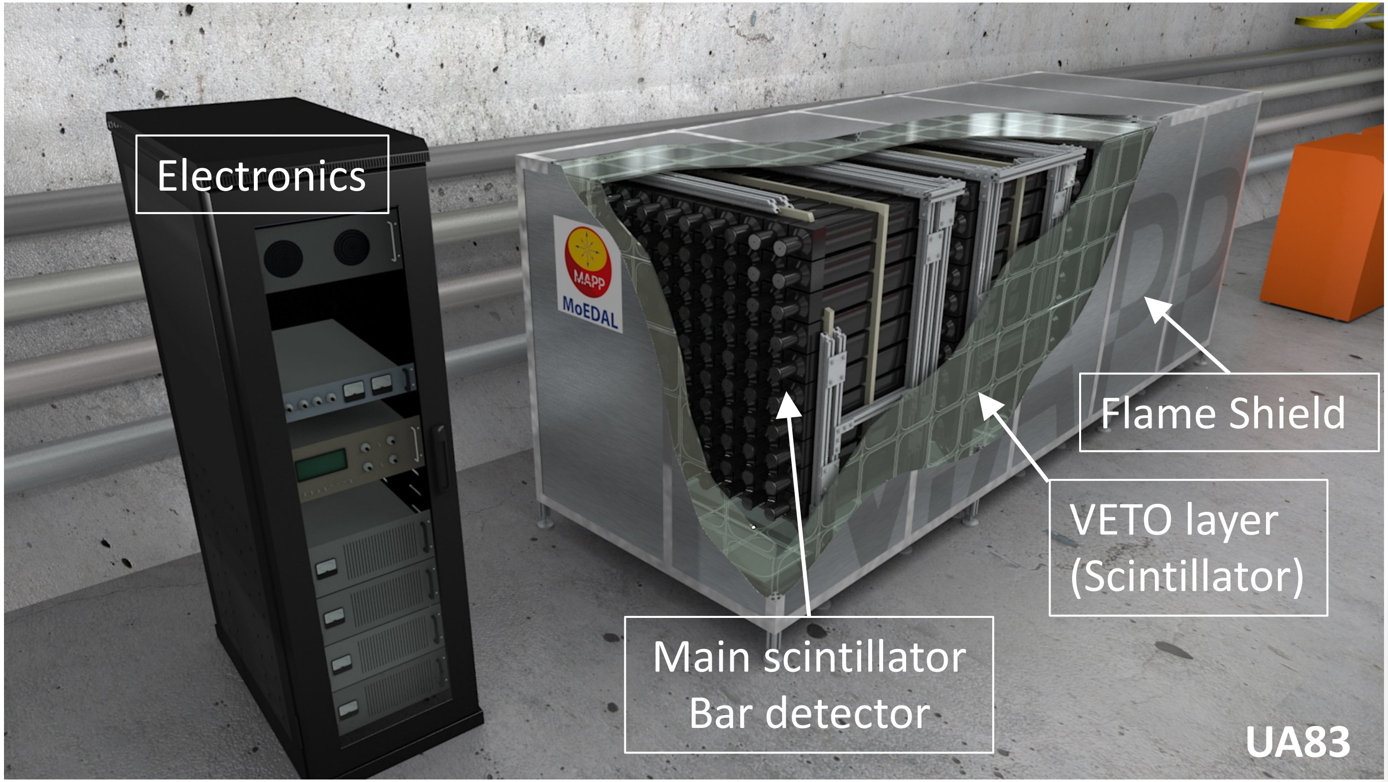
MAPP location

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



MAPP-mQP Phase-1 detector concept

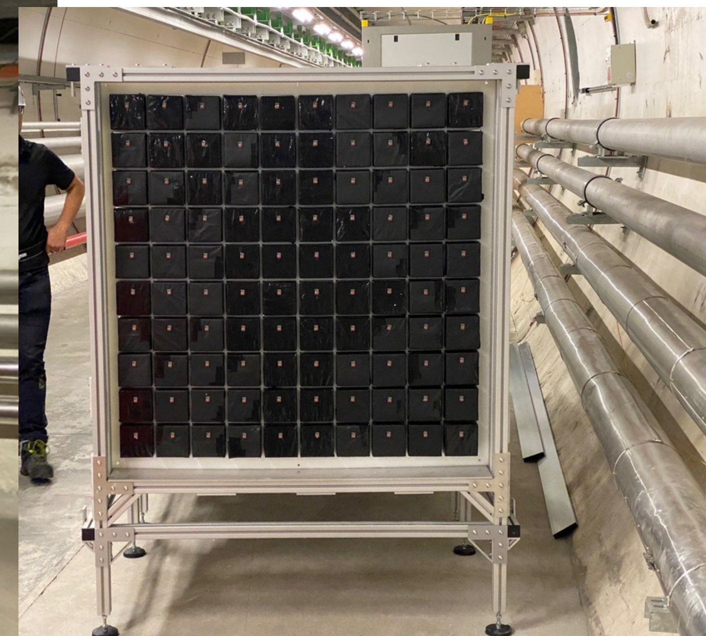
MAPP
MoEDAL



Prototype mQP in 2017 in UGC1 gallery

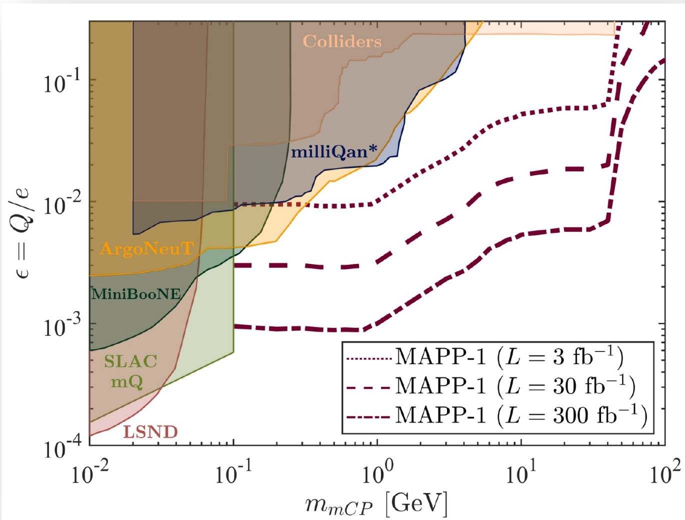
- 400 scintillator bars ($10\times10\times75$ cm^3) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

MAPP-mQP Phase-1 installation



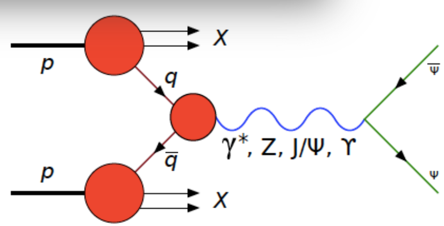
Millicharged particles

Dark photon decays to mCPs

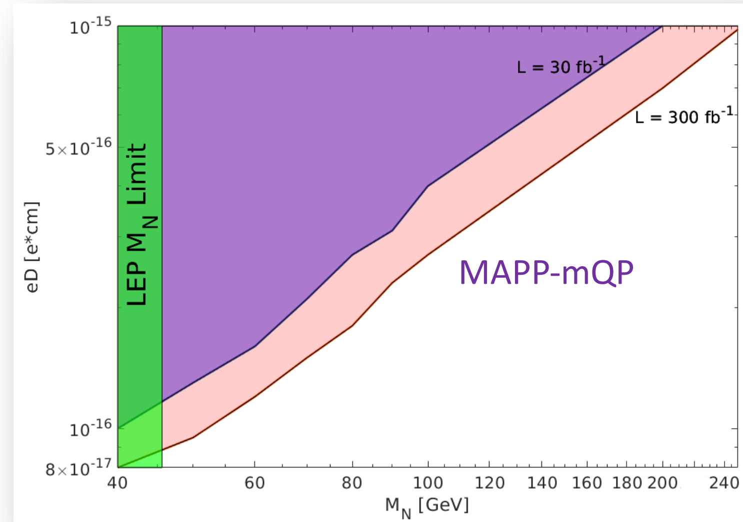


M. Staelens, PhD thesis, U. Alberta, DOI: 10.7939/r3-g8yh-hv16 (2021)

Run-3 sensitivity for dark-photon models giving rise to mCP dark fermions ψ



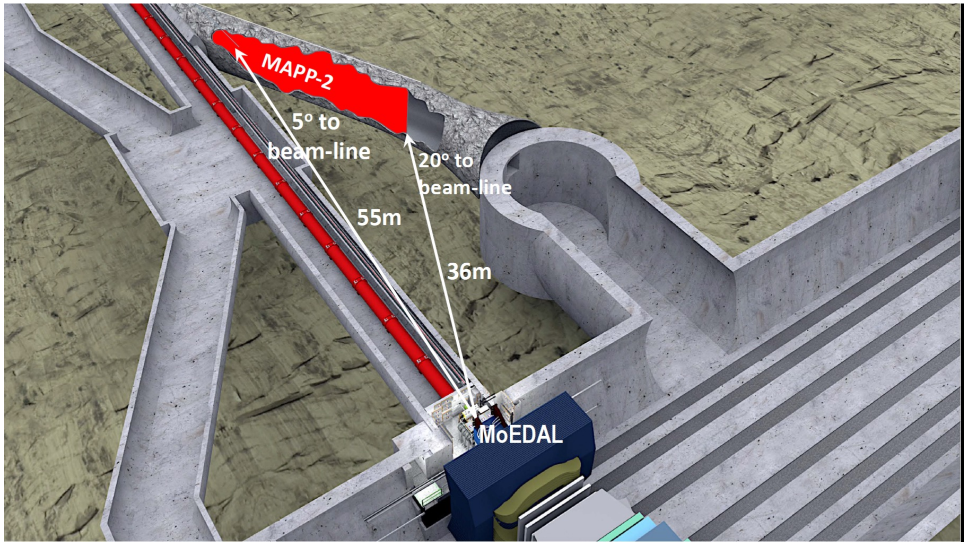
Heavy neutrino with large EDM

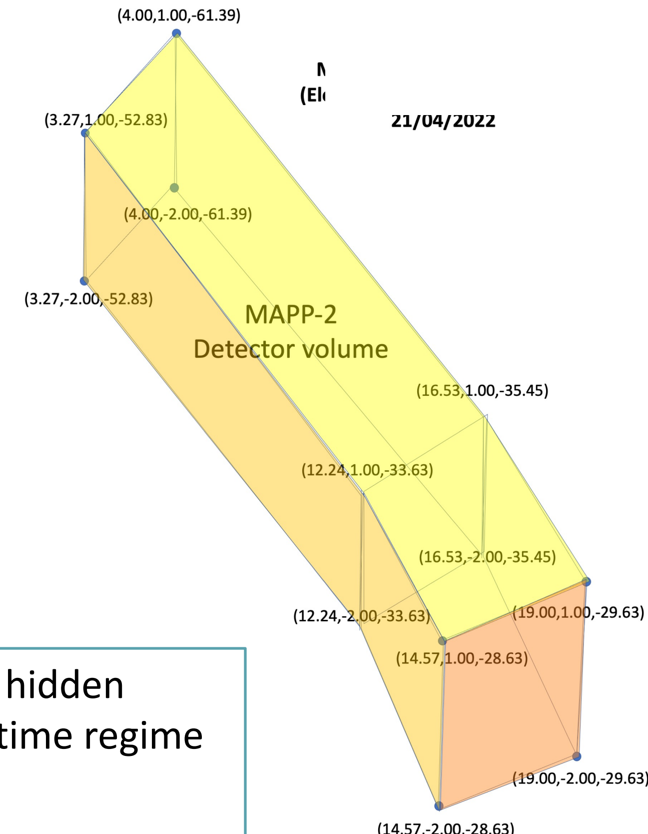


Frank et al, Phys.Lett.B 802 (2020) 135204

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

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

MAPP-LLP will explore hidden sectors in the long-lifetime regime
- dark photons
- dark Higgs bosons
- heavy neutral leptons
- axions & ALPs

Summary & outlook

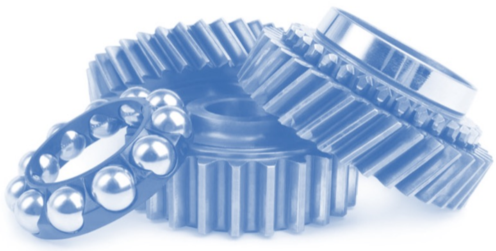
MoEDAL

- 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**
- 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, ...

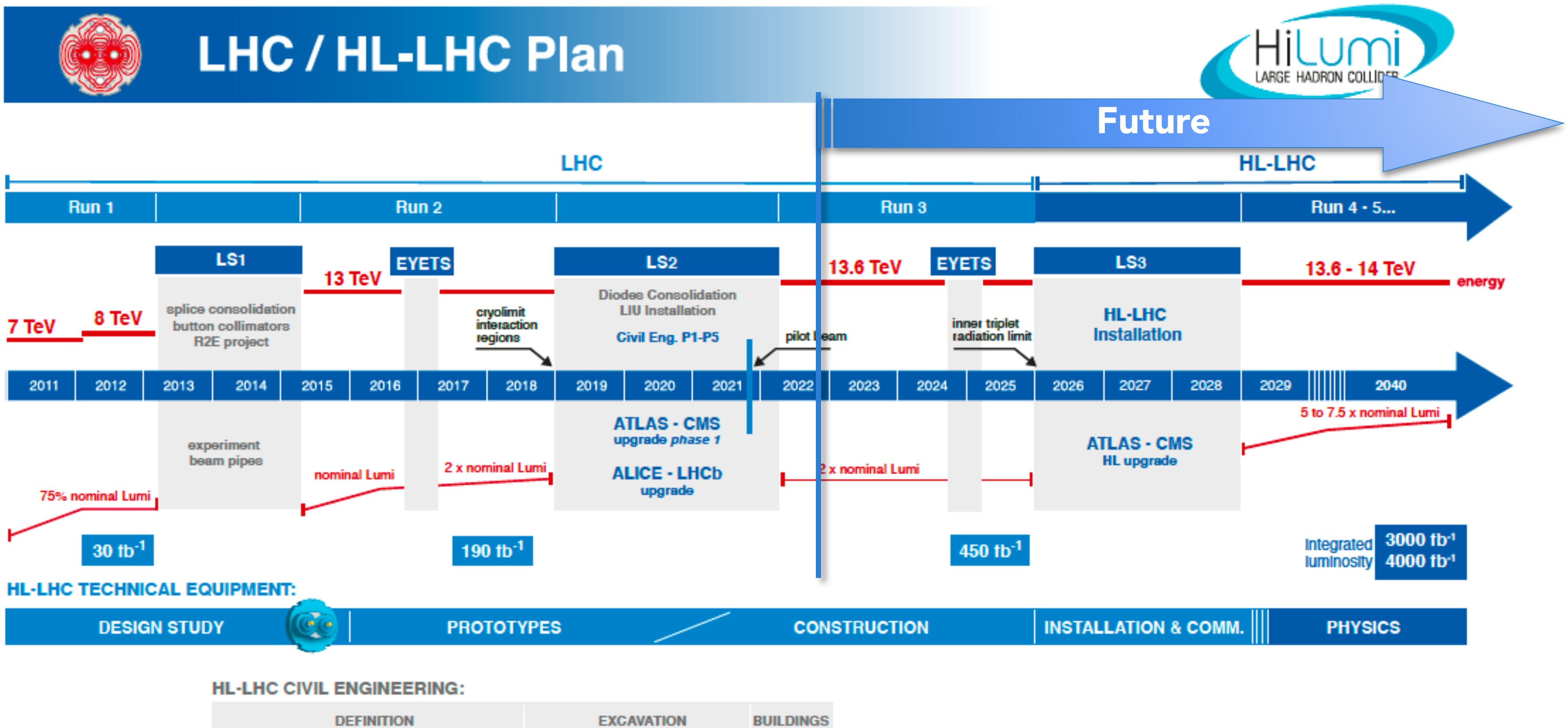
See also: MoEDAL contribution to Snowmass Summer Study, arXiv:2209.03988 [hep-ph]

Thank you for your attention!

Spares



LHC & High Luminosity LHC (HL-LHC)



Energy loss

$$\frac{\text{charge}}{\text{velocity: } \beta = v/c} = z/\beta$$

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

Electric charge

Bethe-Bloch formula

High ionisation (HI) possible when:

- multiple electric charge
- very low velocity & electric charge
- magnetic charge (monopoles, dyons) = ng_D = n × 68.5 × e
  - a singly charged relativistic monopole has ionisation ~4700 times MIP!!
- any combination of the above

$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I_m} + \frac{K|g|}{2} - \frac{1}{2} - B(g)\right]$$

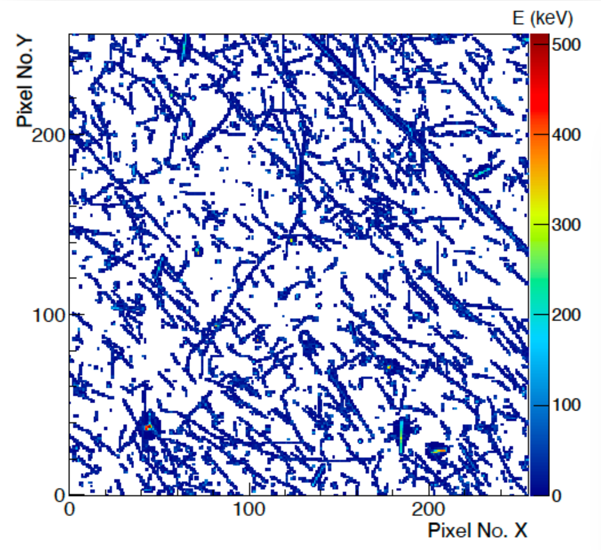
Magnetic charge

Ahlen formula

TimePix radiation monitor

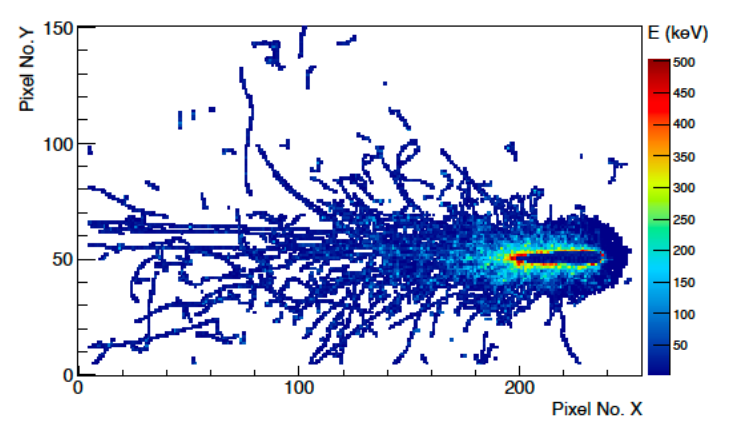
- Timepix chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic "bubble-chambers"
- The only active element in MoEDAL

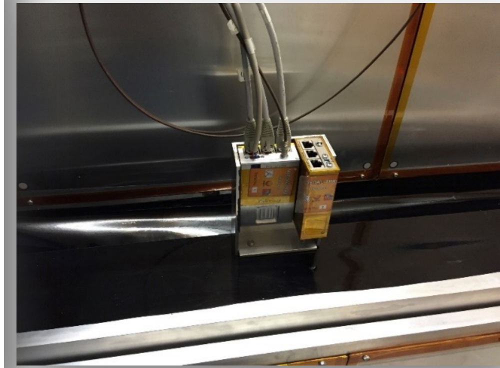
- 256×256 pixel with 55 μm pitch
- Time-of-interaction precision 1.56 ns
- 3D track reconstruction
- Energy deposition measured via time-over-threshold
- Particle ID through *dE/dx*



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

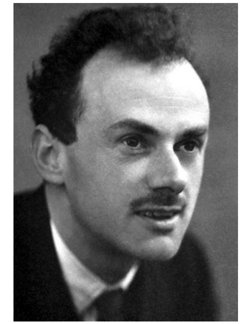
330 GeV Pb-ion measured at the SPS

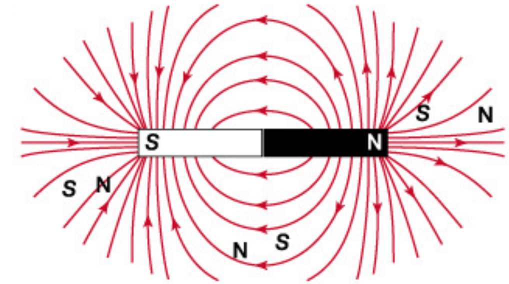




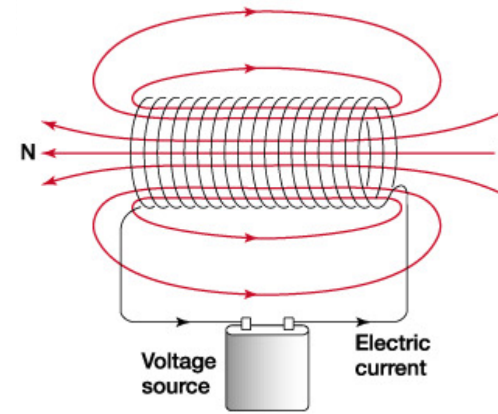
MoEDAL, PoS ICHEP2020 (2021) 720

Dirac's monopole





- Paul Dirac in 1931 hypothesised that magnetic monopoles exist
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid



- Dirac's quantisation condition:

$$ge = \left[\frac{\hbar c}{2}\right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad \left(from \quad \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

  - where **g** is the **magnetic charge** and α is the fine structure constant 1/137

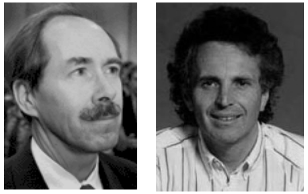
- This means that **g = 68.5e,** when n=1
- If magnetic monopole exists then charge is quantised:

$$e = \left[\frac{\hbar c}{2g}\right] n$$

Dirac string

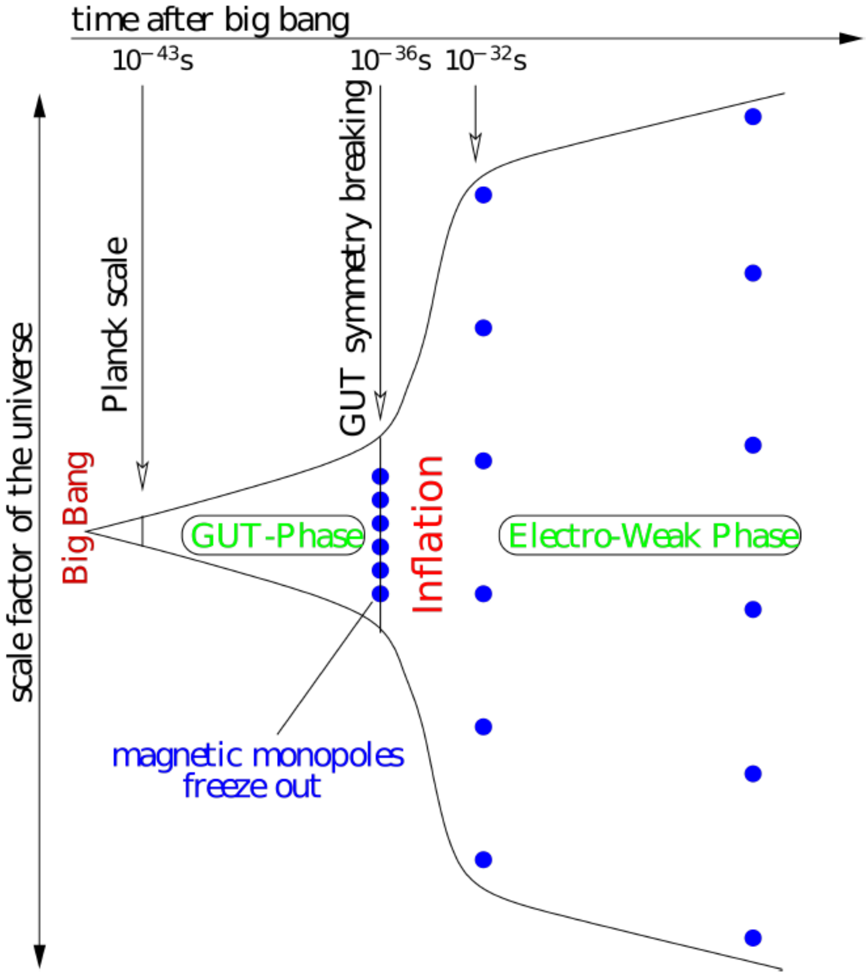
GUT monopoles

- 't Hooft and Polyakov (1974) showed that monopoles are fundamental solutions to non-Abelian gauge grand unification theories (GUTs)



- **Topological solitons**: stable, non-dissipative, finite-energy solutions
- Mass:
  - **10^{13} GeV < *M* < 10^{19} GeV**
  - in intermediate stages of symmetry breaking: **10^{7} GeV < *M* < 10^{13} GeV**

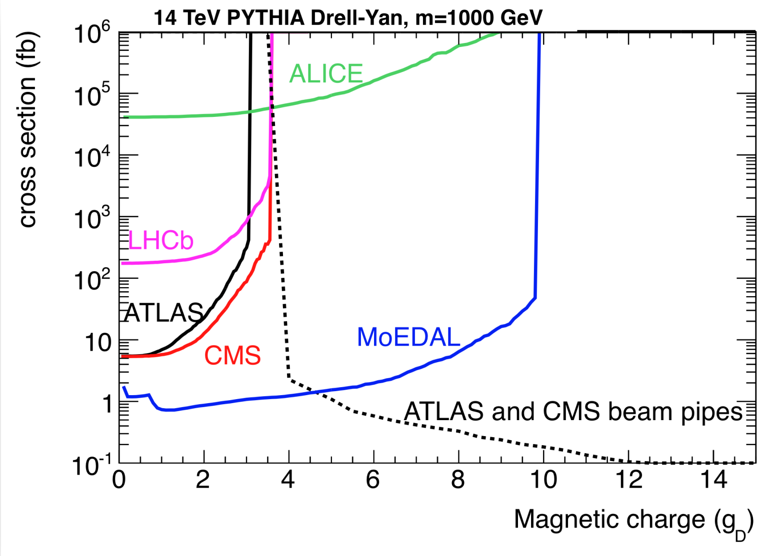
  → cannot be produced in accelerators
- Size: **extended object**
  - radius > few femtometers



T. Glüsenkamp 10

CMS beam pipe

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



De Roeck et al, EPJC72 (2012) 1985

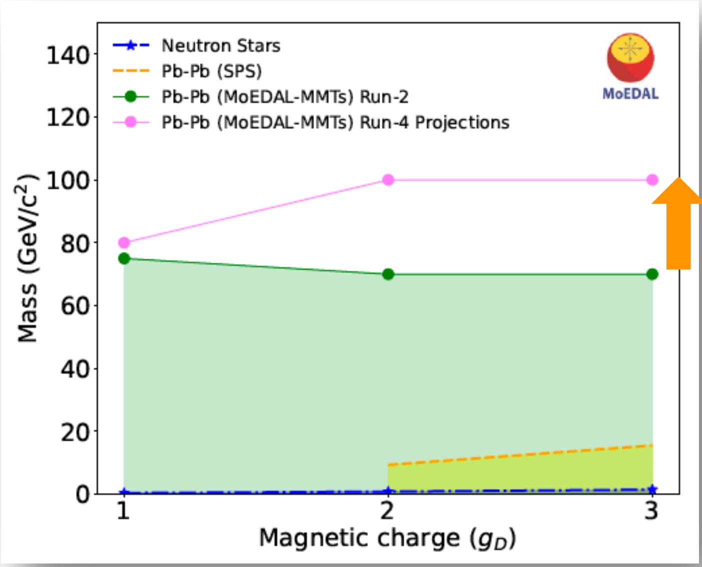
- **1990's:** materials from CDF, D0 (Tevatron) and H1 (HERA) subject to SQUID scans for trapped monopoles
- **2012:** first pieces of CMS beam pipe tested [EPJC72 (2012) 2212]; far from collision point
- **Feb 2019:** CMS officially transfers ownership of the Run-1 CMS beam pipe to MoEDAL

CERN Courier, Mar-Apr 2019

Beam pipe scanned with SQUID at ETH Zurich
Interpretation in progress

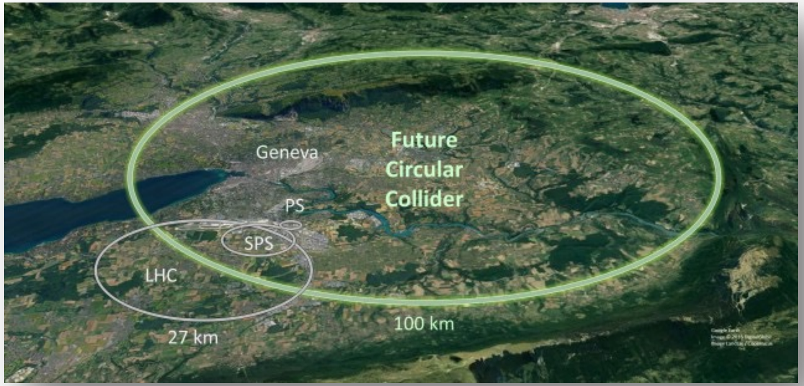
Schwinger production: future prospects

- Analysis of full NTD data from Run-2 heavy-ion collisions
- HL-LHC projection for MoEDAL's MMTs
  - Conservative theoretical assumptions
  - Nuclear track detectors not included in projection
  - Assuming 2.5 nb^{-1} Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.52 TeV



~20 GeV increase in sensitivity in HL-LHC heavy-ion run

Opportunities for new physics searches with heavy ions at colliders, Snowmass 2021, arXiv:2203.05939



For FCC : $\sqrt{s_{NN}} \sim 40$ TeV
$\Rightarrow M \gtrsim 600$ GeV

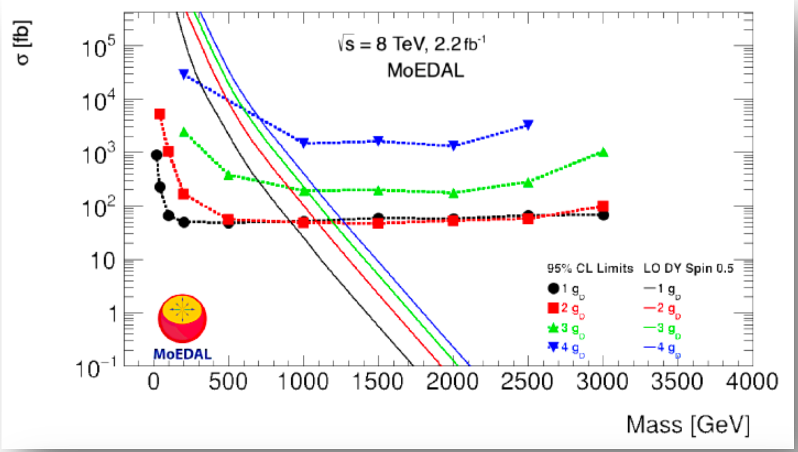
Theoretical improvements in semiclassical and fully classical approaches

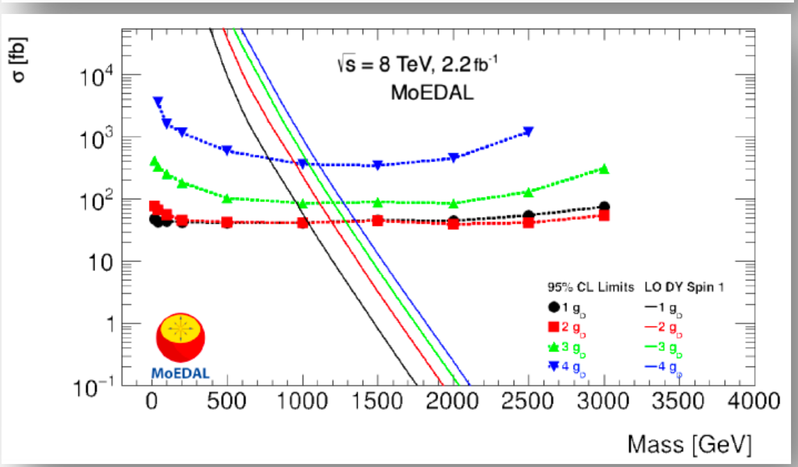
NTD+MMT results – monopoles

- Limits on DY production of magnetic monopole pairs with cross-section in the range of **~40 fb – 5 pb** were set for magnetic charges up to **$4g_D$** and mass as high as **1.2 TeV**
- Monopole limits not competitive with recent Run-2 collider limits due to
  - limited acceptance of MMT and NTD Run-1 prototype detectors compared to Run-2
  - smaller √s, hence DY cross-section at Run-1
  - lower integrated luminosity of Run-1 compared to Run-2

	Magnetic charge (g_D)			
	1	2	3	4
Spin	95% CL mass limits [GeV/c^2]			
0	590	740	710	520
1/2	910	1090	1020	700
1	1030	1190	1190	1110

MoEDAL, Eur.Phys.J.C 82 (2022) 694



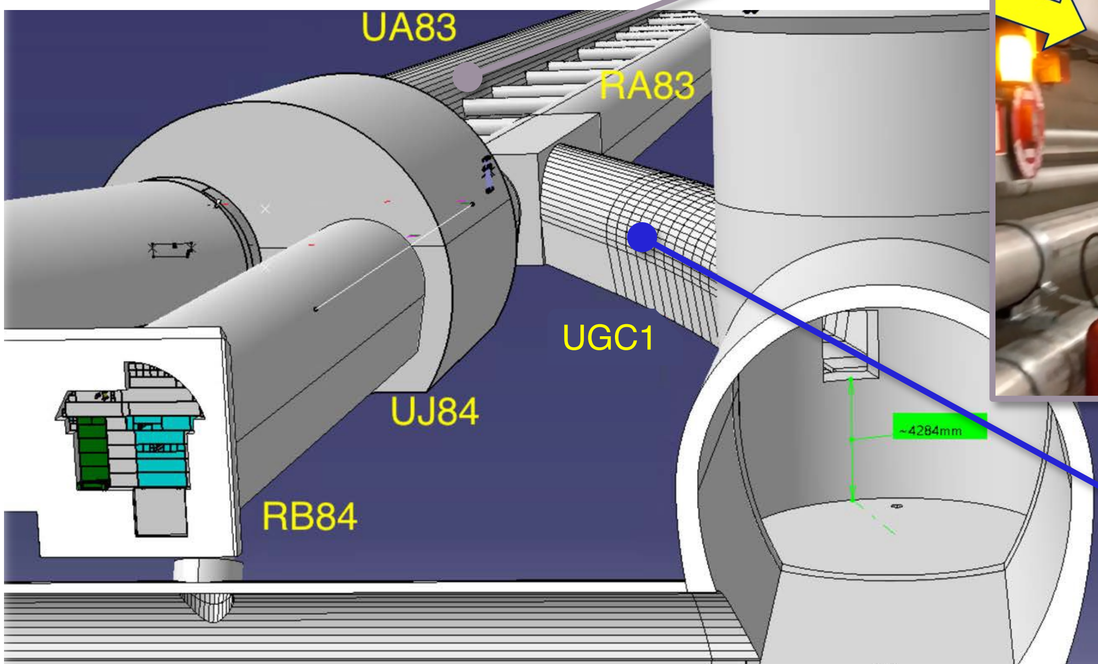


MAPP locations

MAPP MoEDAL

UA83

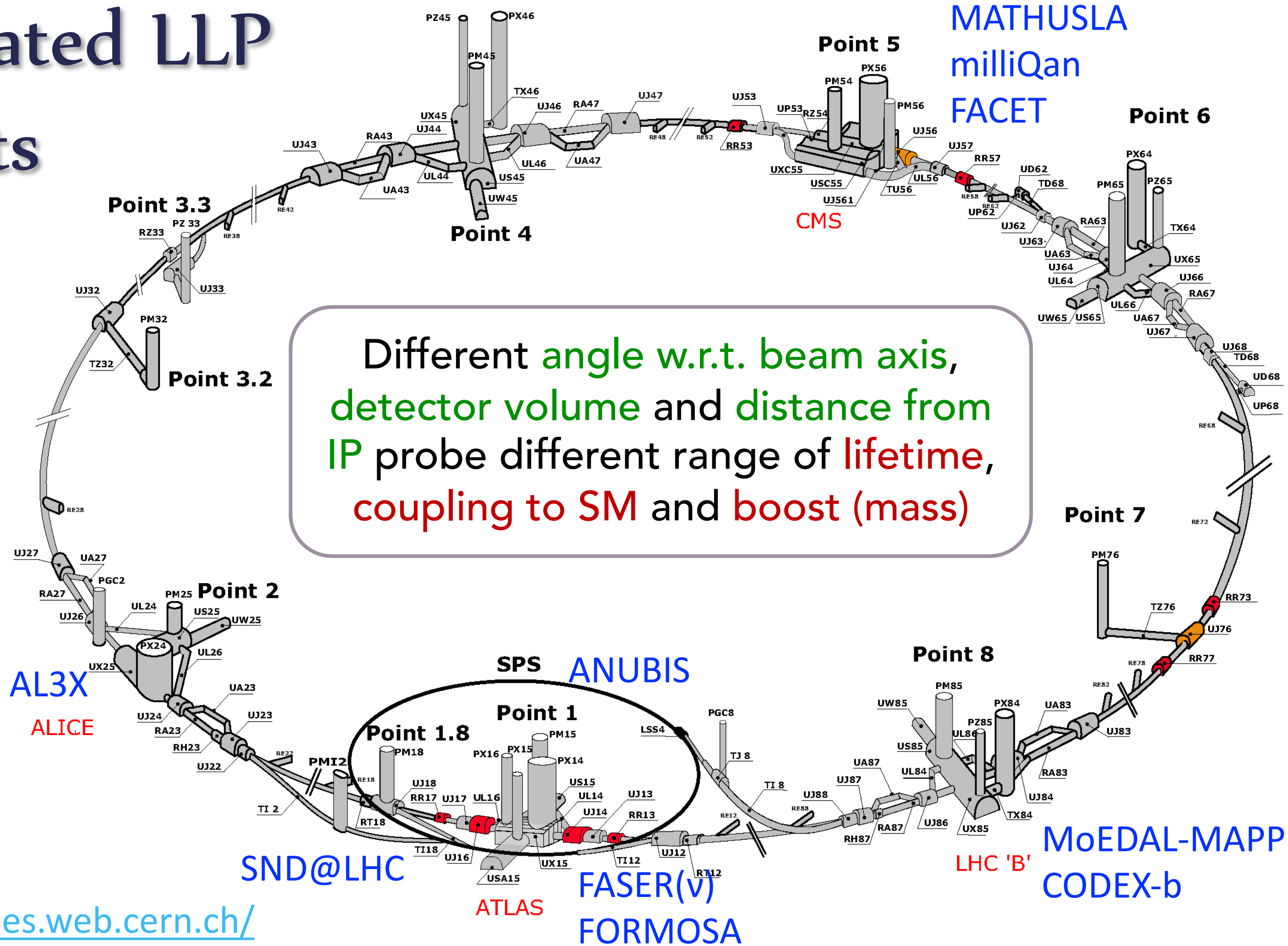
- mQP location
- 100 m from IP8 at ~7° to the beam
- Easily accessible gallery, already fitted out
- Access independent from LHCb



- mQP 2017 prototype location
- Extensive engineering required
- To be ready for MAPP LLP during HL-LHC

UGC1

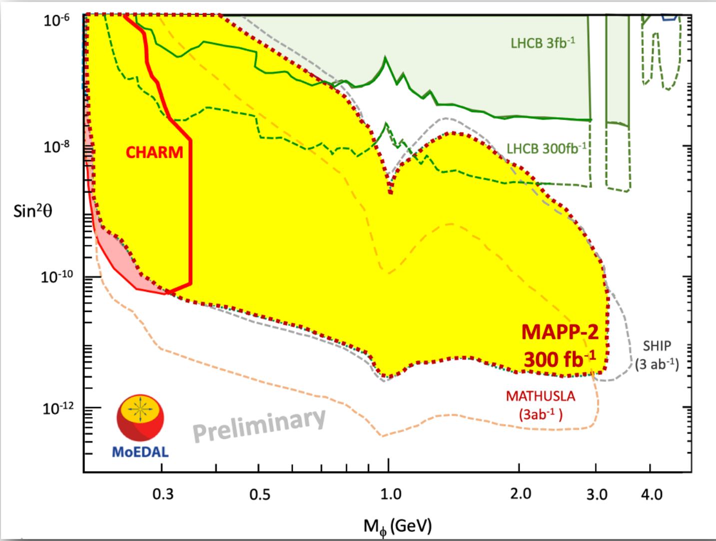
LHC dedicated LLP experiments



LHC-LLP Community
https://longlivedparticles.web.cern.ch/

MAPP-LLP – dark matter & heavy neutrinos

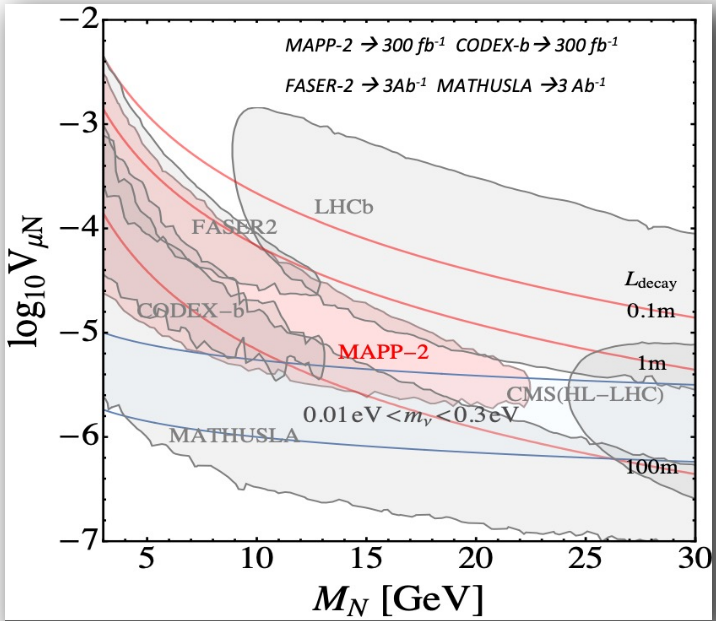
Dark Higgs scenario



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]