Recent updates from MoEDAL

Emanuela Musumeci (Alabama U.)

on behalf of the MoEDAL collaboration

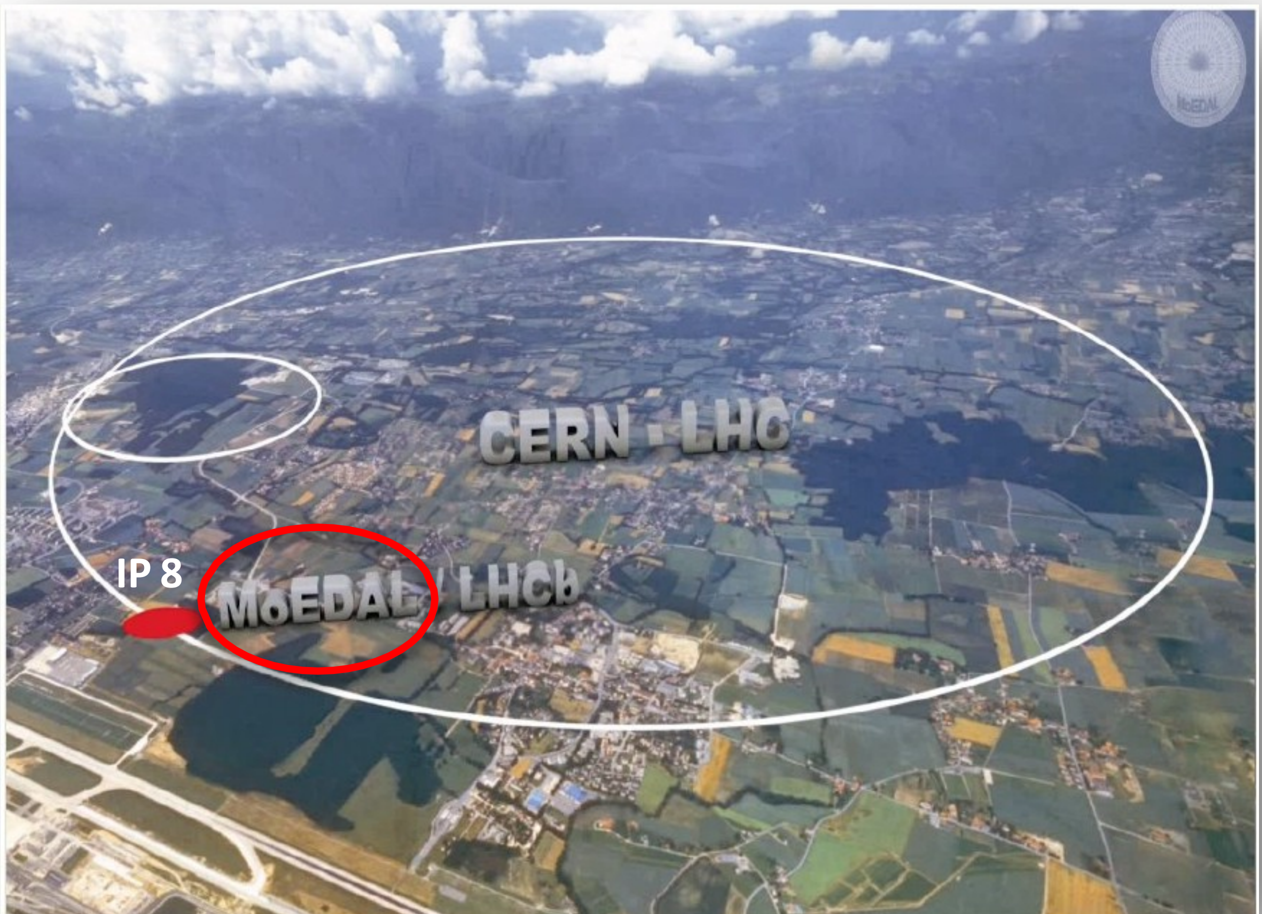
XXII CPAN Days

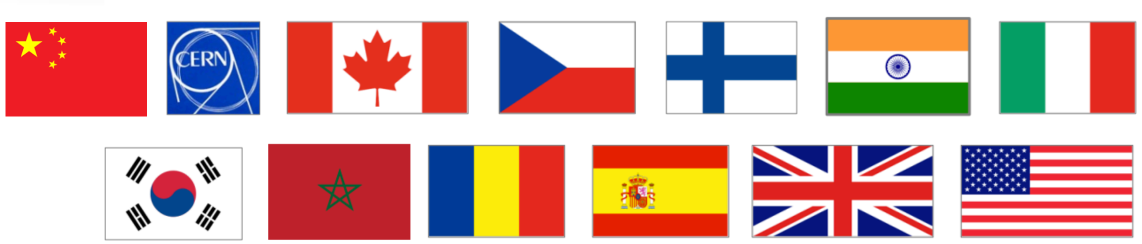
20/11/2025

THE MoEDAL EXPERIMENT

Monopole & Exotics Detector At LHC

MAPP
MoEDAL





~60 physicists from 18 institutions

- UNIVERSITY OF ALABAMA
- UNIVERSITY OF ALBERTA
- INFN & UNIVERSITY OF BOLOGNA
- UNIVERSITY OF BRITISH COLUMBIA
- INSTITUTE OF PHYSICS, UNIVERSITY OF HELSINKI
- CERN
- CONCORDIA UNIVERSITY
- IMPERIAL COLLEGE LONDON
- KING'S COLLEGE LONDON
- NATIONAL INSTITUTE OF TECHNOLOGY, KURUKSETRA
- MOHAMMED PREMIER UNIVERSITY, OUJDA, MOROCCO
- IEAP, TECHNICAL UNIVERSITY IN PRAGUE
- QUEEN MARY UNIVERSITY OF LONDON
- INSTITUTE OF SPACE SCIENCE, ROMANIA
- CENTER FOR QUANTUM SPACETIME, SEOUL
- TUFT'S UNIVERSITY
- IFIC VALENCIA
- IHEP BEIJING

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

Highly Ionising Particles

HIPs are characterised by their exceptional ability to ionise detector materials

Bethe-Bloch formula

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi N_A r_e^2 m_e c^2}{A} \frac{Z}{\beta^2} z^2 \left[\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 \right]$$

- $-\frac{\mathrm{d}E}{\mathrm{d}x}$ is the mean energy loss per unit distance
- z is the charge number of the incident particle
- Z and A are the atomic and mass number of the absorber material
- N_A is Avogadro's number
- r_e is the classical electron radius
- m_e is the electron mass
- c is the speed of light in vacuum
- $\beta = \frac{v}{c}$ is the particle's velocity
- $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ is the Lorentz factor
- I is the mean excitation potential of the material

Electrically charged particles can only cause significant ionisation if they are either very massive and moving slowly or if they carry multiple charges.

Magnetic Monopoles

- Explanation of the discrete nature of the electric charge

Dirac Quantisation Condition

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

- $\alpha \equiv \frac{e^2}{4\pi\epsilon_0}$ *Fine Structure Constant*
- $g = n g_D, \ n \in \mathbb{N}$ *Magnetic Charge*
- $g_D \equiv \frac{e}{2\alpha}$ *Fundamental Dirac Charge*

Dirac Monopole

- point-like particle
- *spin* and *mass* are free parameters

- Symmetrised Maxwell's equations invariant under rotations in (**E**, **B**) plane

Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla} \cdot \vec{E} = 4\pi\rho_e$	$\vec{\nabla} \cdot \vec{E} = 4\pi\rho_e$
Gauss' law for magnetism:	$\vec{\nabla} \cdot \vec{B} = 0$	$\vec{\nabla} \cdot \vec{B} = 4\pi\rho_m$
Faraday's law of induction:	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi\vec{J}_m$
Ampère's law (with Maxwell's extension):	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi\vec{J}_e$	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi\vec{J}_e$

Electric-Magnetic Duality

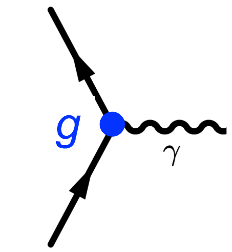
Other Models:

- GUT monopoles ’
  G. 't Hooft, *Nucl. Phys. B79, 276* (1974),
  A. M. Polyakov, *JETP Lett. 20, 194* (1974)
- Electroweak monopoles
  J.Ellis, N. Mavromatos, T.You, *Phys.Lett.B* 756 (2016) 29-35
- Monopolium
  Epele, Fanchiotti et al., *EPJ Plus 127* (2012) 60

Magnetic Monopoles

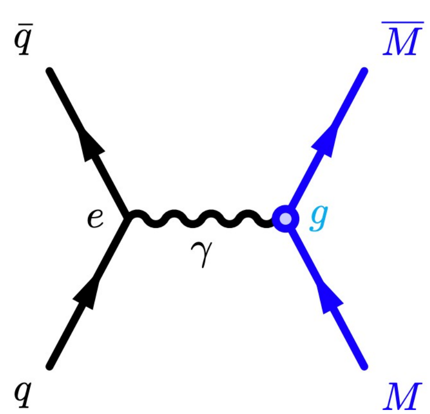
One would expect that monopoles could be produced by similar electromagnetic processes that produce pairs of electrically charged particles.

Monopole-photon coupling g is analogous to the electron-photon one

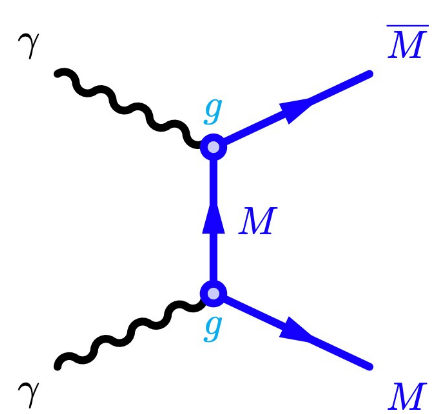


Production mechanisms at **colliders**

Direct

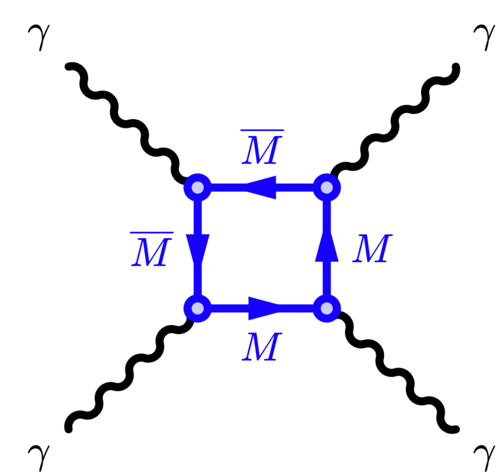


Drell-Yan like

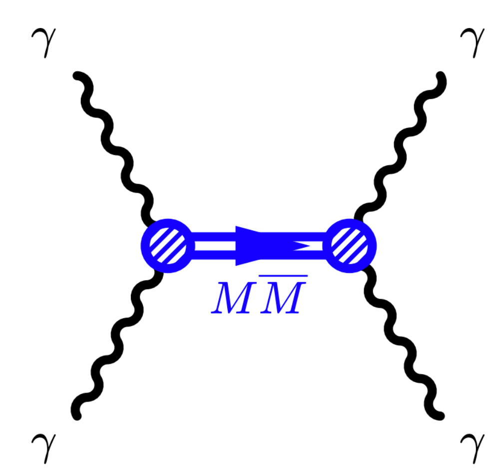


Photon Fusion

Indirect



Monopole box diagram



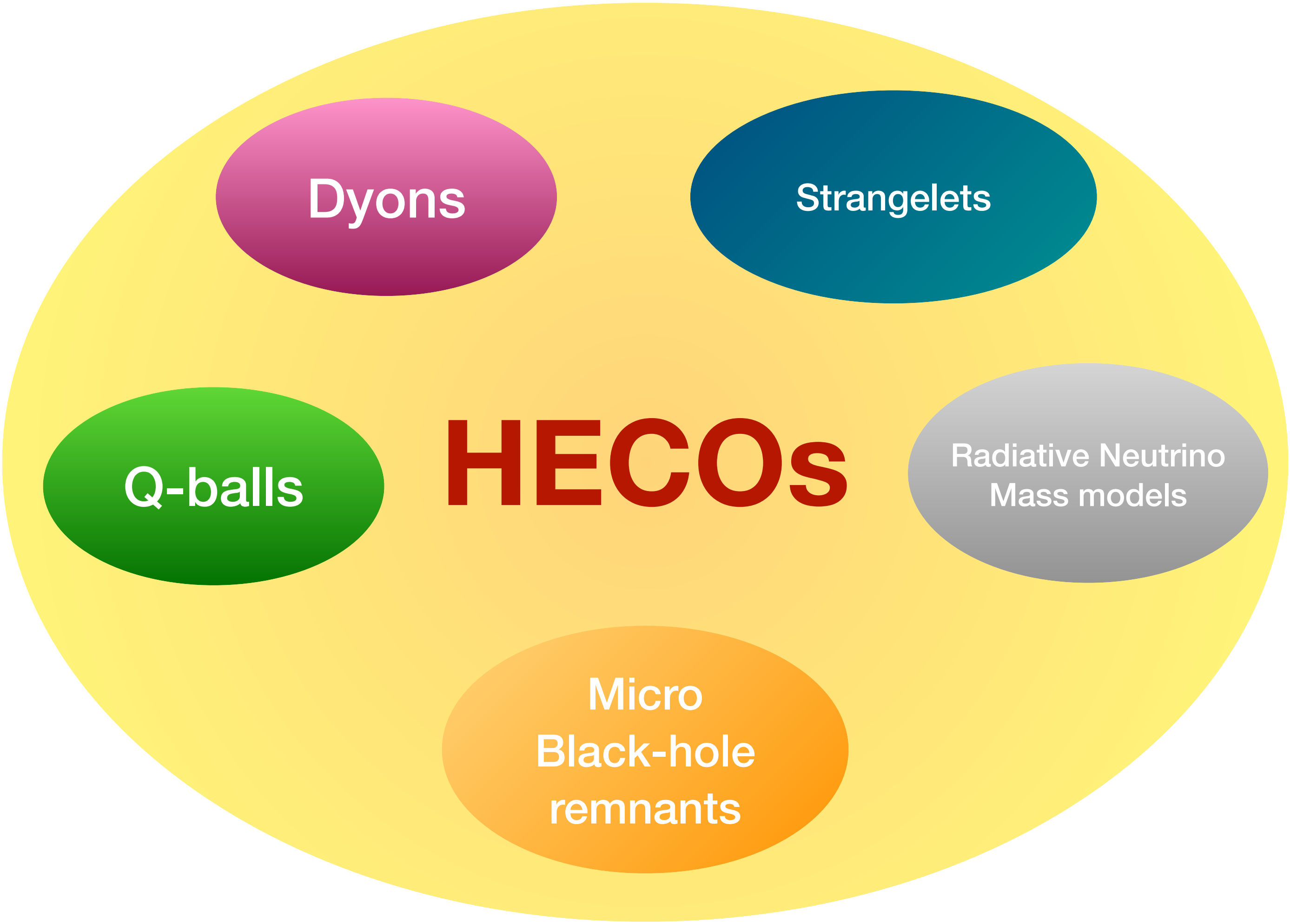
Monopolium production

N.Mavromatos & V.Mitsou,
Int.J.Mod.Phys.A 35 (2020) 2030012

There are different models of MMs predicting masses at the electroweak scale and thus relevant to colliders

High Electric Charge Objects

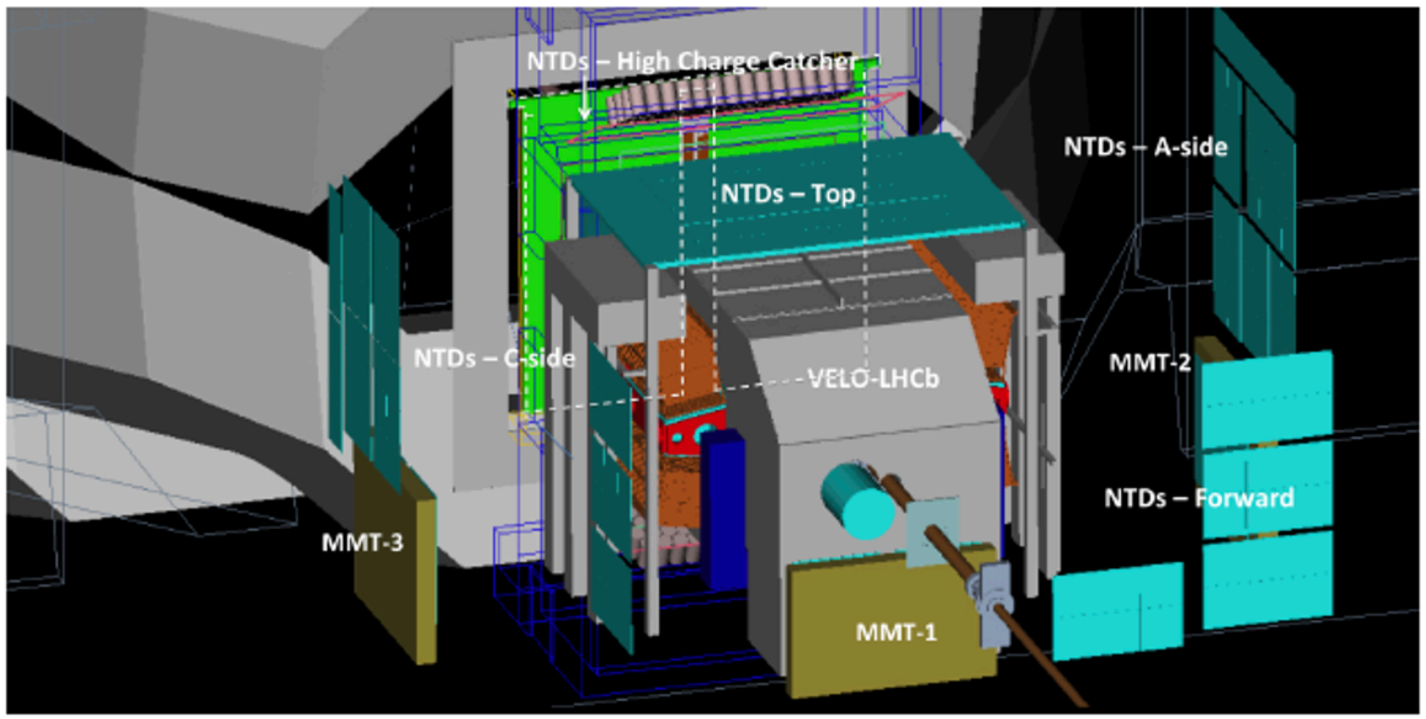
Predicted by various theories Beyond the Standard Model



- **Q=** $ne, \ n \in \mathbb{Z}$
- High Ionisation
- Mass and Spin are *free parameters*
- Same production mechanisms at colliders as monopoles

THE MoEDAL EXPERIMENT

The MoEDAL detector



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

The Detectors

1. ***Nuclear Track Detectors (NTDs)*** *- (Makrofol/CR39/ Lexan sheets) highly ionising particles will leave characteristic tracks*

2. ***Magnetic Monopole Trappers (MMTs)*** *- Al trapping volumes, monopole would bind to matter*

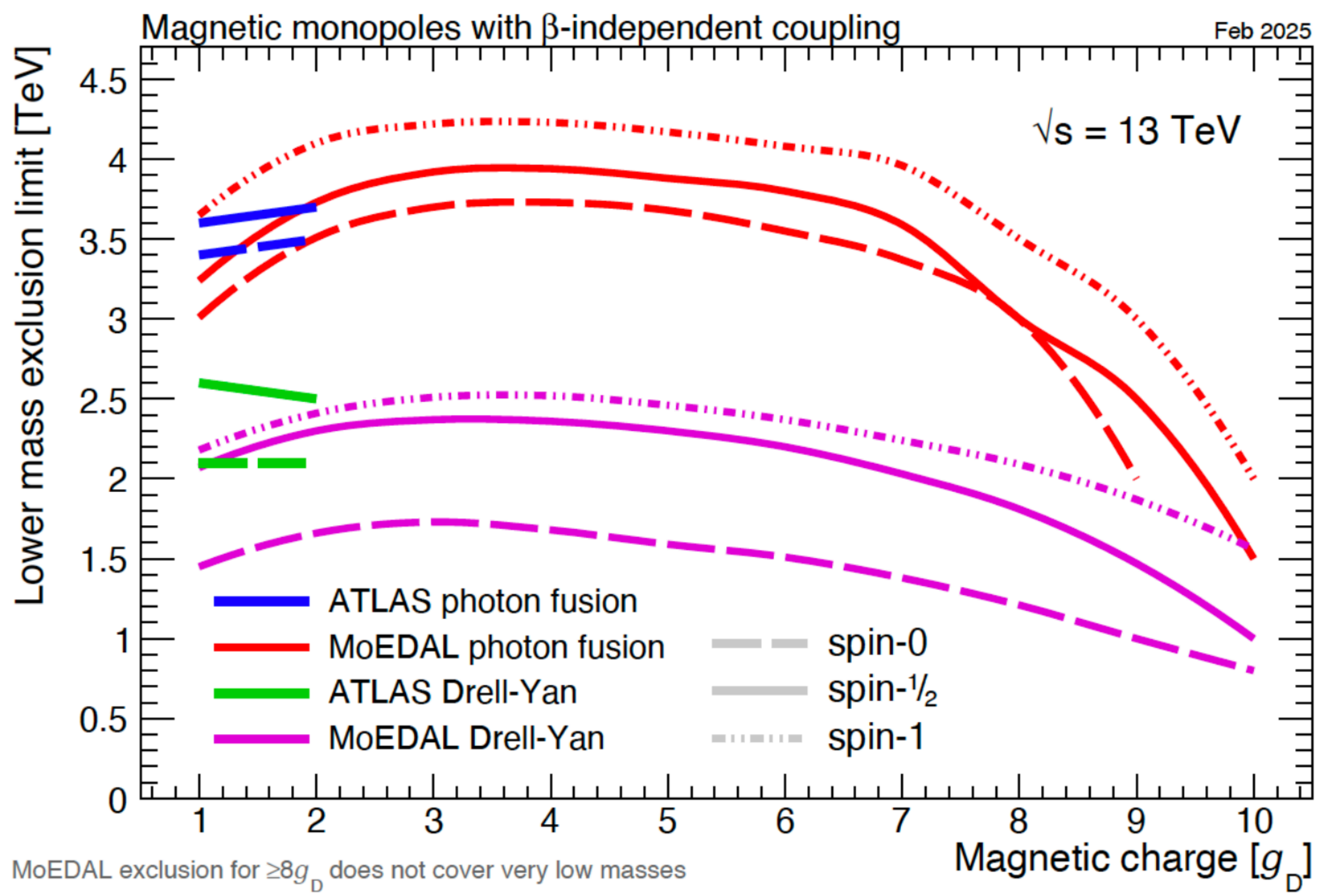
3. ***TimePix detector array*** *- monitors the background radiation in real-time.*

MAGNETIC MONOPOLES LIMITS

MoEDAL introduced novelties, pushing the theory of MMs as much as the experiment

- γγ fusion
- spin-1 monopoles
- β-dependent coupling

$(\beta = \sqrt{1 - 4M^2/s})$



Complementarity MoEDAL↔ATLAS

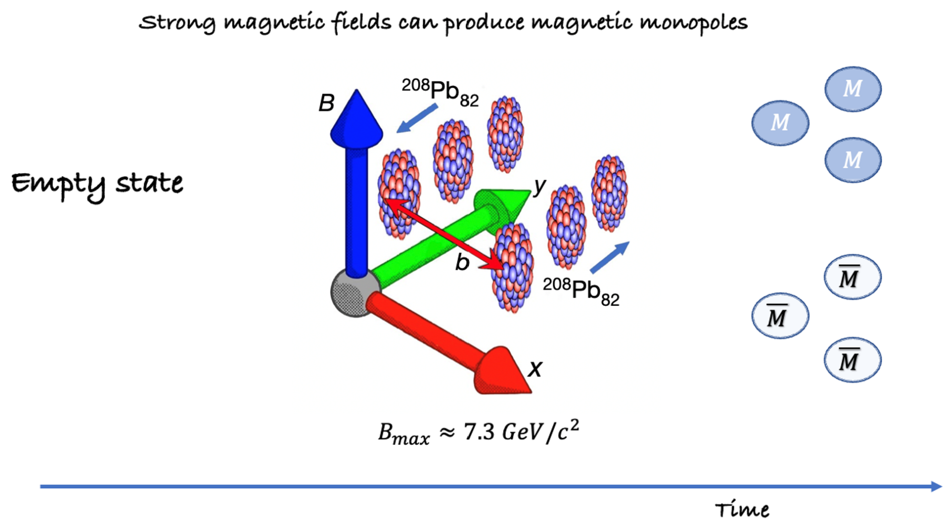
MoEDAL set world-best collider limits for |g| > 2 g_D

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, PRL 134 (2025) 071802

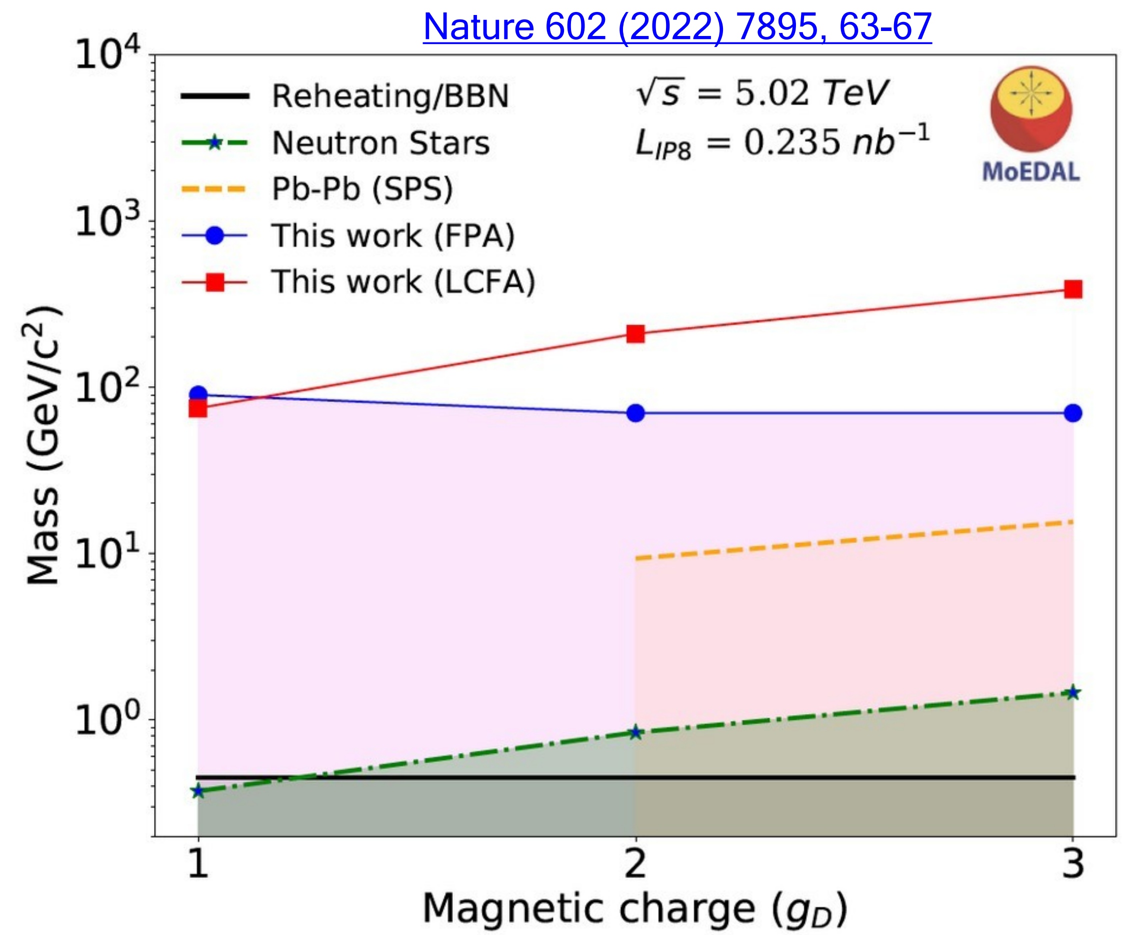
⚠ Mass bounds obtained using perturbative Feynman-like diagrams, which fail to account for the intrinsically non-perturbative monopole–photon interaction.

MAGNETIC MONOPOLES LIMITS

Monopoles via Schwinger mechanism



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

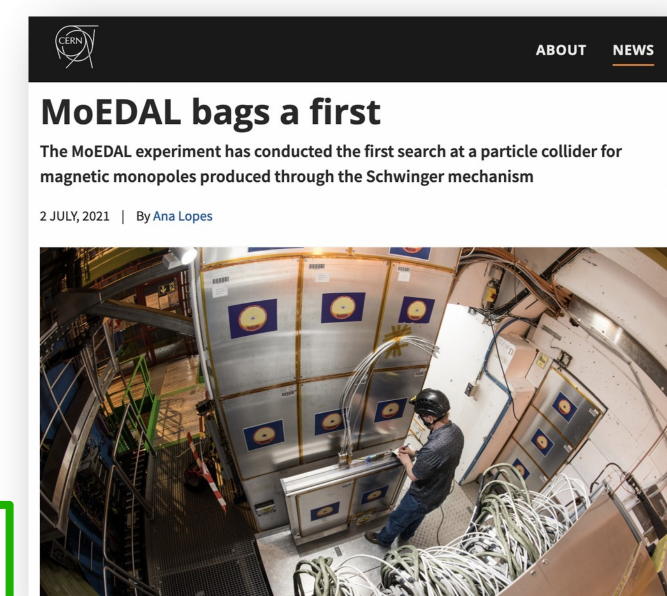


The 2018 LHC Pb-Pb run

– CM energy of 5.02 TeV per collision

– 880 kg of MoEDAL's MMTs exposed to integrated luminosity of 0.235 nb^{-1}

- No statistically significant signal observed
- The existence of a monopole with g > 0.5 g_D in the trapping volume was excluded at more than 3σ



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

MAGNETIC MONOPOLES LIMITS

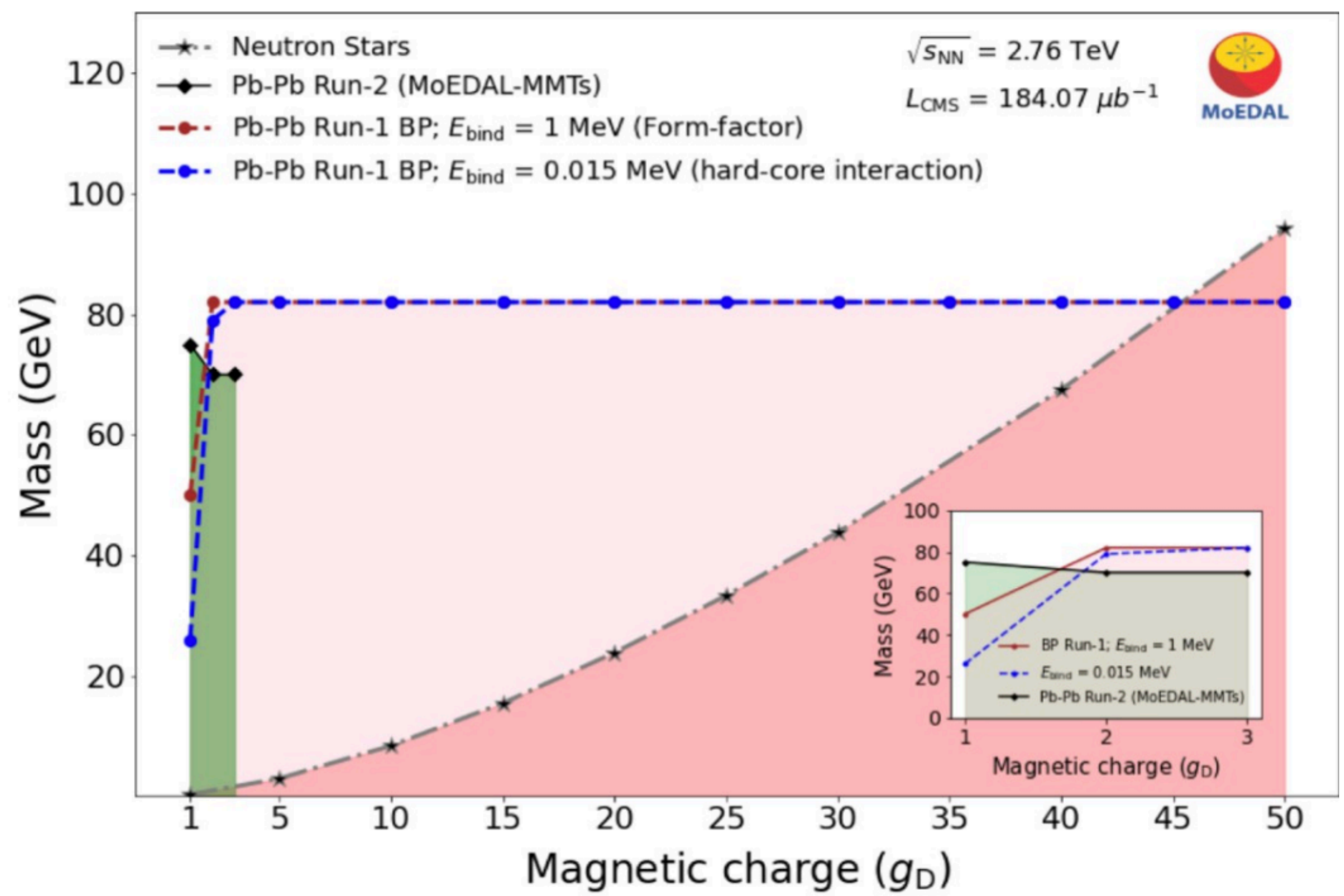
Monopoles via Schwinger mechanism & CMS beam pipe

The CMS pipe was exposed to PbPb collisions during Run-1

It was donated to MoEDAL, crashed, and searched with a SQUID magnetometer for the presence of trapped magnetic charge

- most directly exposed piece of material
- Scanned for presence of trapped monopoles by MoEDAL Collaboration
- No signal was found, setting the first reliable mass limits on monopoles with world-leading sensitivity to large magnetic charges
- **Composite** and **point-like** monopoles with masses up to **80 GeV** excluded

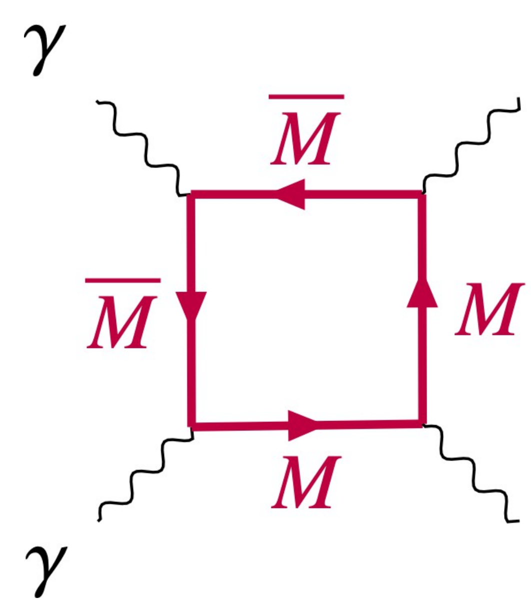
Phys. Rev. Lett. 133, 071803 (2024). PRL Editors suggestion



MAGNETIC MONOPOLES LIMITS

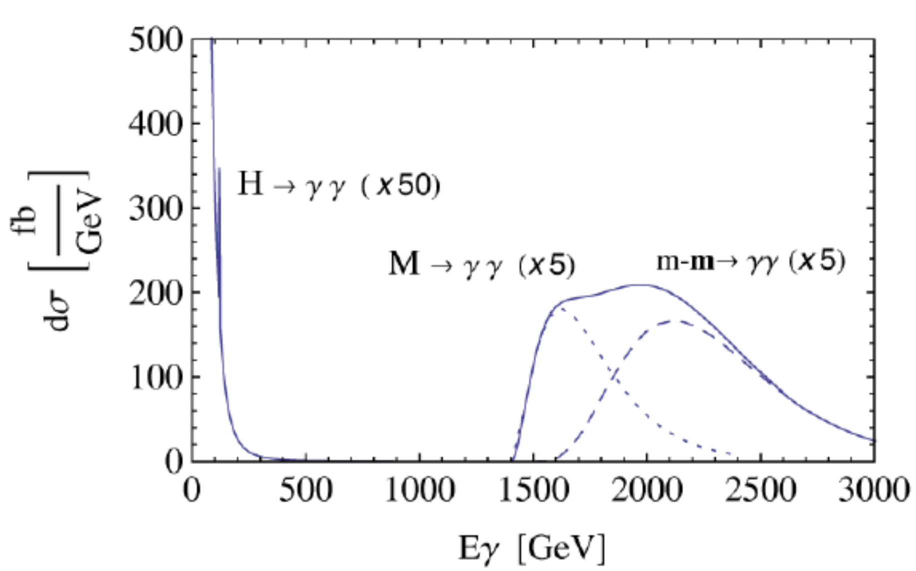
Indirect Production Mechanisms

- Central exclusive γγ production
  - light-by-light scattering in ultraperipheral collisions of heavy-ions
  - in *pp* collisions with proton tagging: PPS (CMS-TOTEM) & AFP (ATLAS) [Fichet, von Gersdorff, Lenzi, Royon, Saimpert, JHEP 02(2015)165]
- Effective Field Theories & Born-Infeld interpretations lead to indirect limits on monopoles [Ellis, Mavromatos, You, PRL 118 (2017) 261802 ; Ellis, Mavromatos, Roloff, You, EPJC 82 (2022) 634]

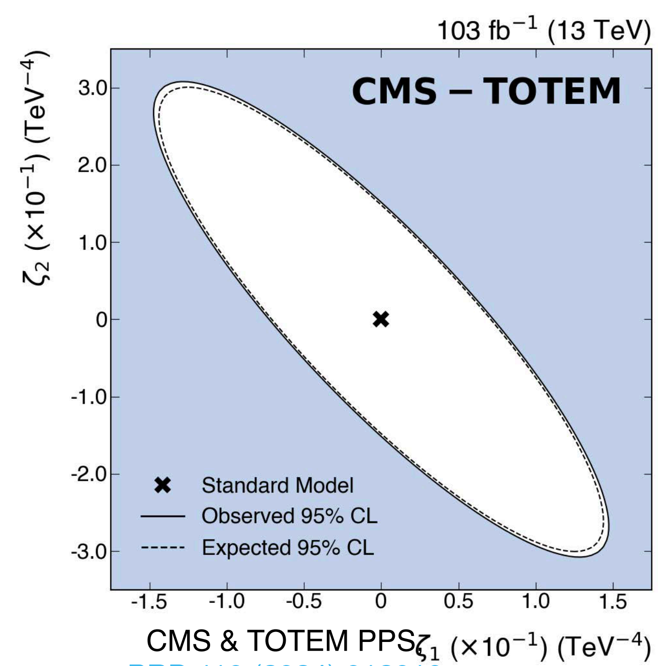


Monopole box diagram

Final state signature of interest



Epele, Fanchiotti, Garcia Canal, Mitsou, Vento, Eur.Phys.J.Plus 127 (2012) 60



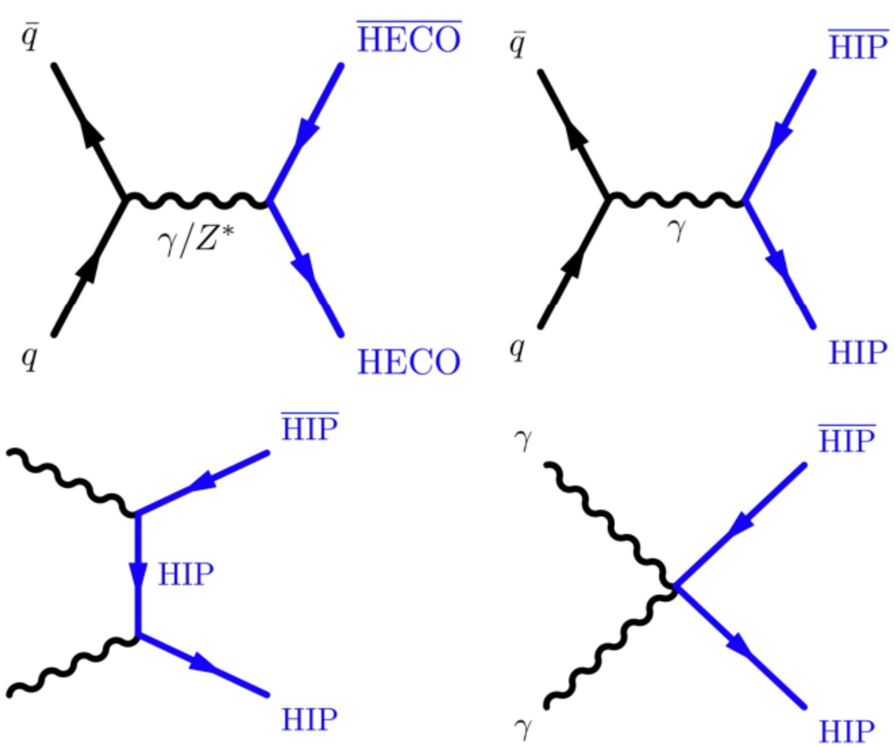
CMS & TOTEM PPS, PRD 110 (2024) 012010

$M_{MM} > 4.05n$ TeV for spin ½

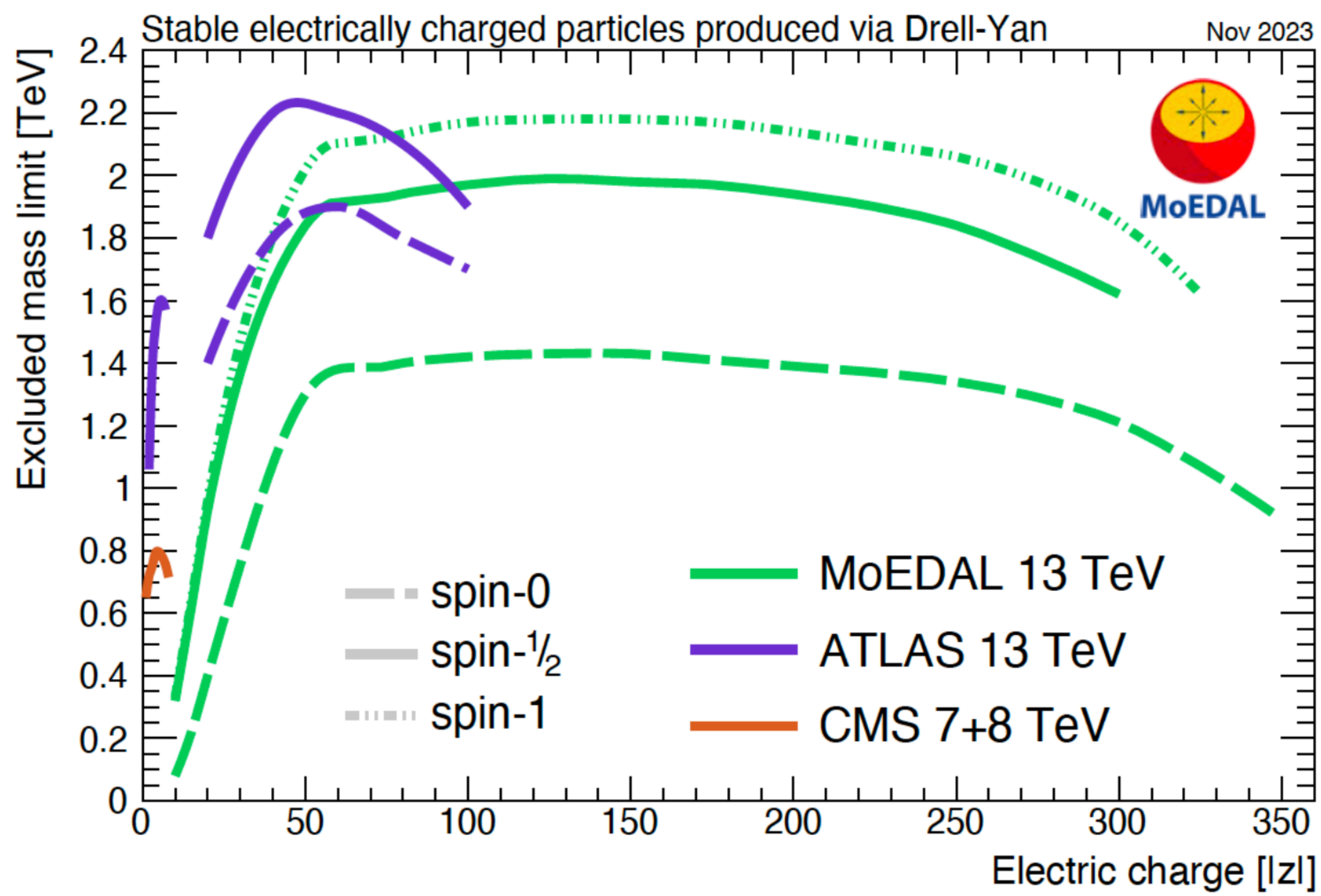
EM & Mitsou, PoS(ICHEP2022)1025
EM, PhD thesis, Valencia U, 2025
Mitsou & EM, *in progress*

LIMITS ON HECOs

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



MoEDAL, [Eur.Phys.J.C 82 (2022) 694, PRL 134 (2025) 071802]

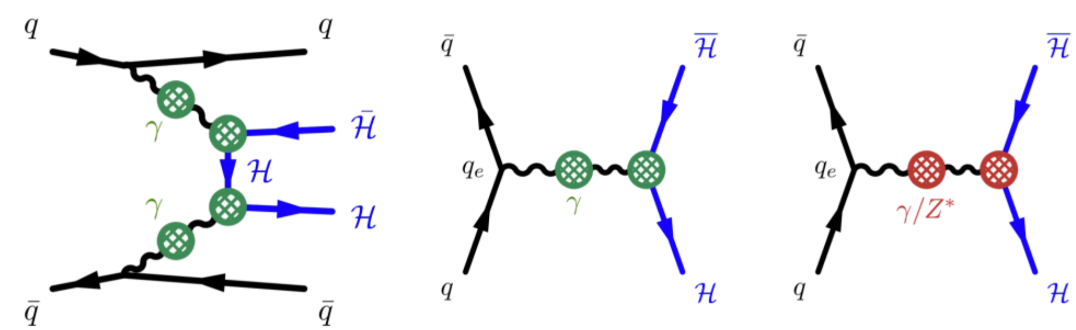


MoEDAL HECOs limits strongest to date, in terms of charge, at any collider experiment

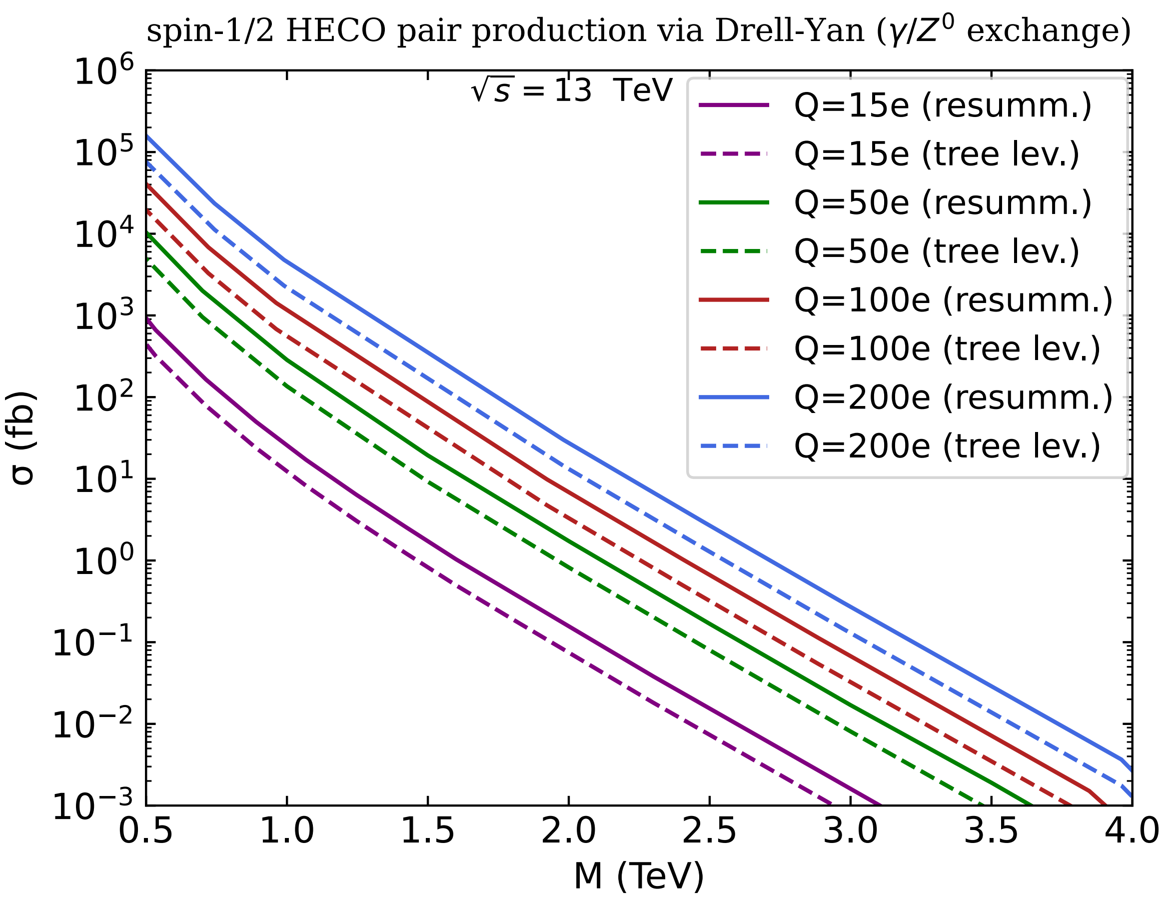
RESUMMATION

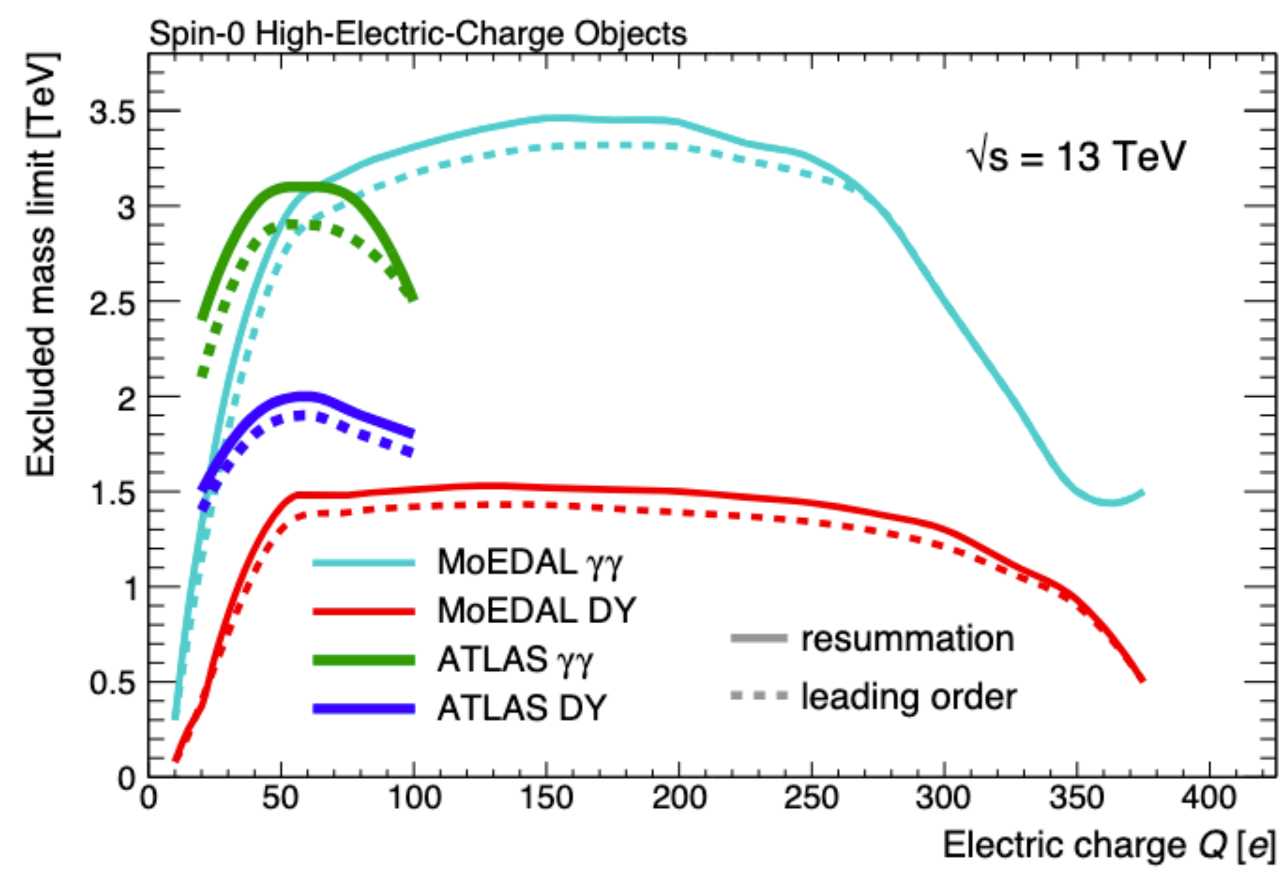
Large coupling g → Perturbation theory breaks down → **Resummation needed!**

Dyson-Schwinger (DS) resummation for spin-0 and spin-1/2 HECOs
- estimated cross section increases with resummation
- more stringent mass limits from ATLAS and MoEDAL searches



Alexandre, Mavromatos, Mitsou, EM, PRD 109 (2024) 036026 & PRD 111 (2025) 076010





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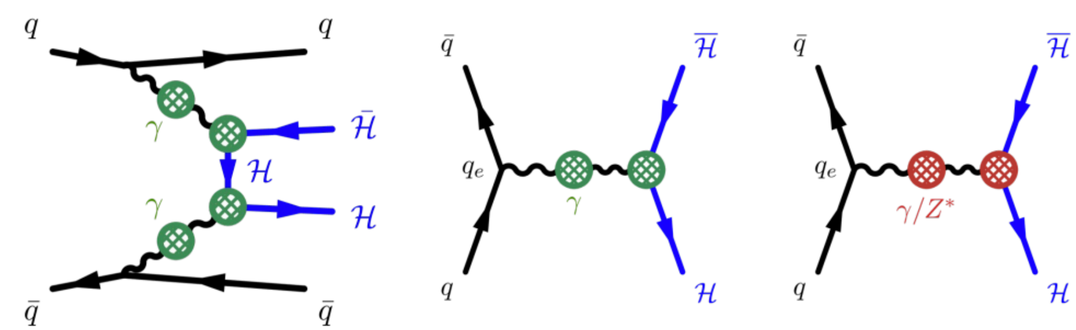
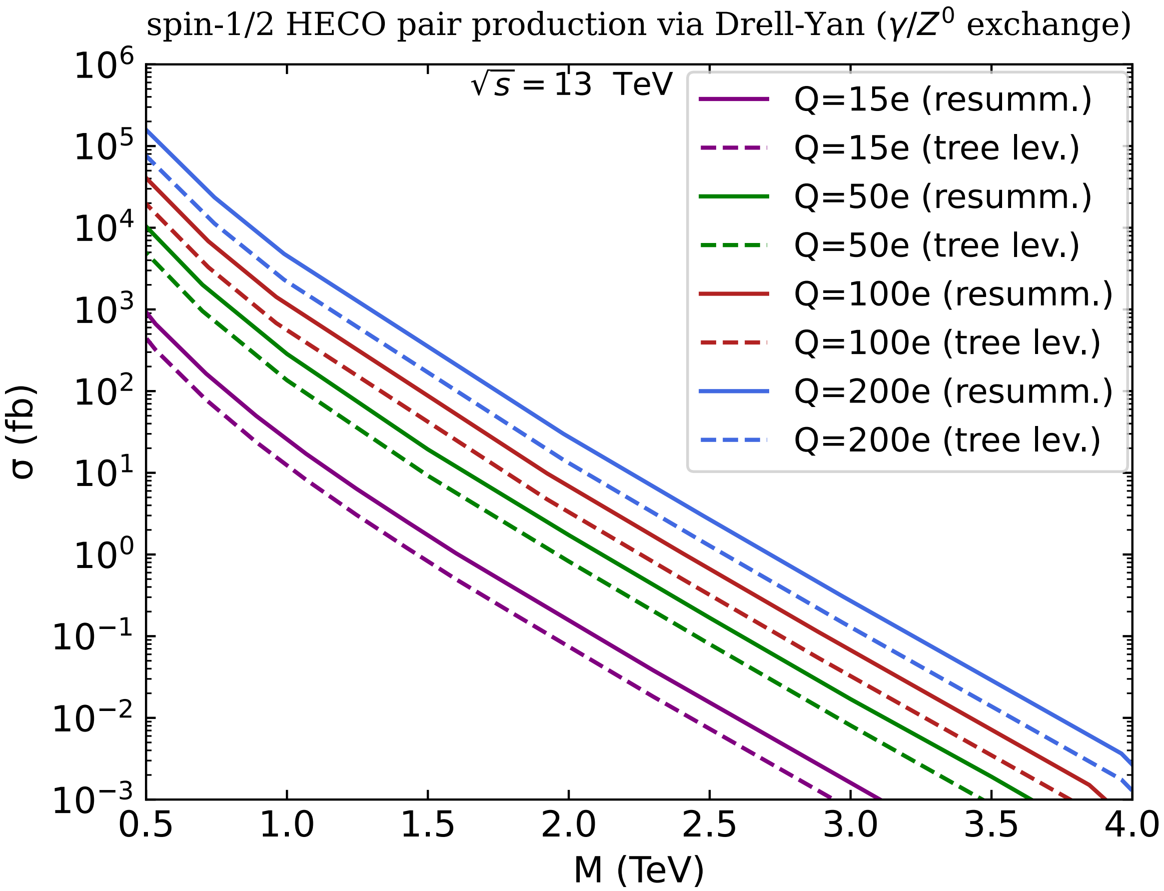
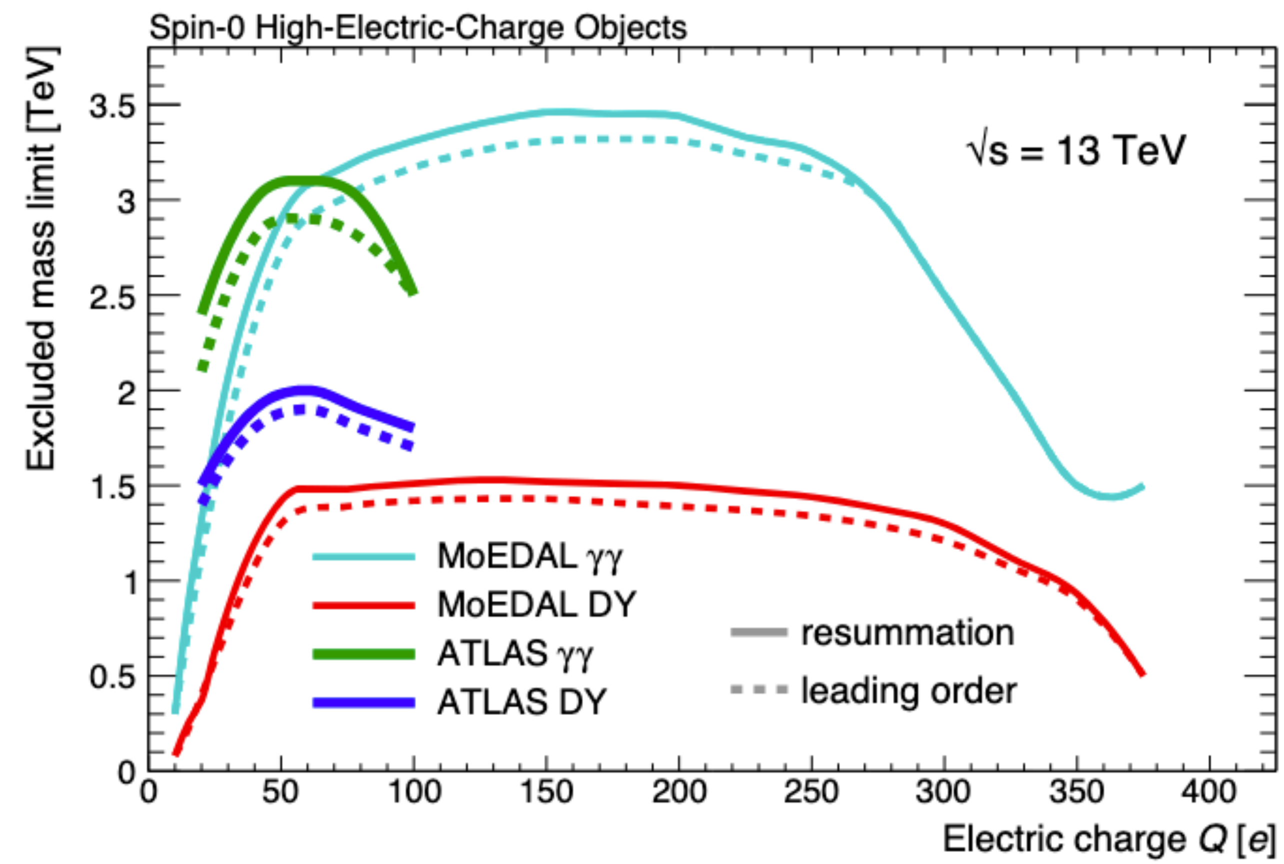


Alexandre, Mavromatos, Mitsou, EM, PRD 109 (2024) 036026 & PRD 111 (2025) 076010





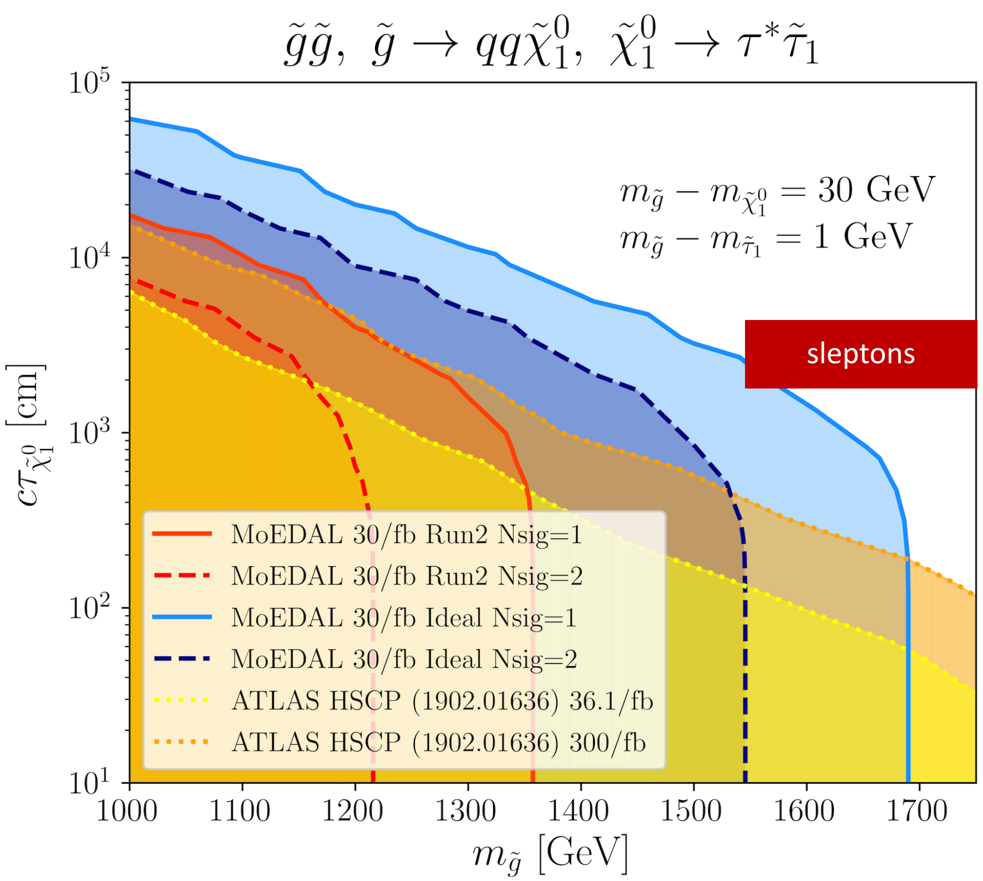
DS Resummation for magnetic monopoles *ongoing*

(Alexandre, Mavromatos, PRD 100 (2019) 096005, Alexandre, Mavromatos, Mitsou, EM, *in progress*)

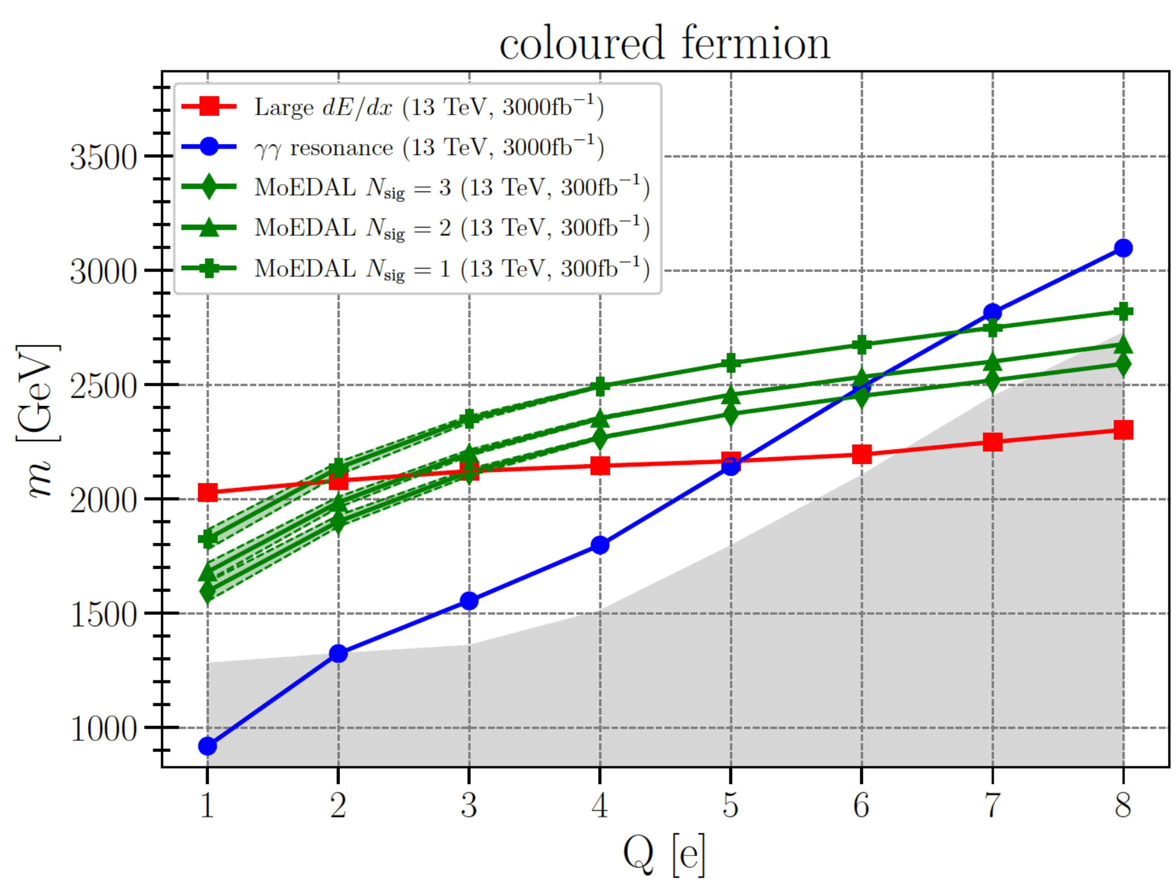
"Low" electric charges

- Supersymmetric singly charged LLPs: sleptons, R-hadrons, charginos
- **Generic multiply charged particles**

- Require NTDs of low Z/β threshold ➜ **CR39**
- Exposed to Run-2 and Run-3 *pp* collisions
- Recently calibrated [Kalliokoski et al, JINST 20 (2025) P0314]
- Analysis in progress



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



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

With CR-39 NTD data, MoEDAL is expected to have the best sensitivity for intermediate (<~10e) electric charges at HL-HC

MoEDAL APPARATUS for PENETRATING PARTICLES

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

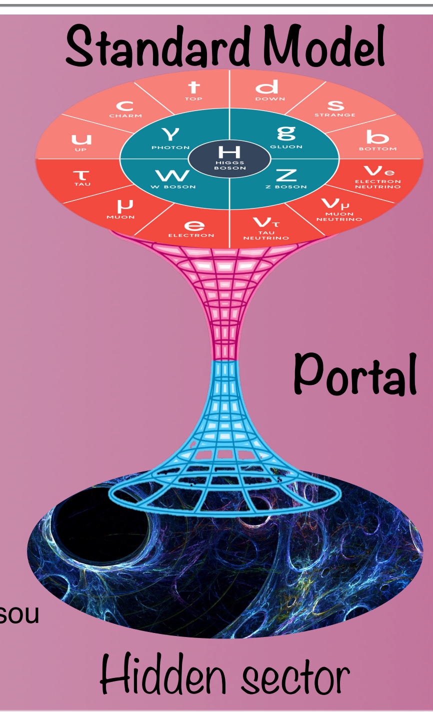
- high charges (**high z**)
  - magnetic ➜ **monopoles**
  - electric ➜ High Electric Charge Objects (**HECOs**)
- slow moving (**low β**) ⇒ massive

Extending the physics program

MAPP designed to expand the search for *new physics* at the LHC

Feebly Interacting Particles (**FIPs**)

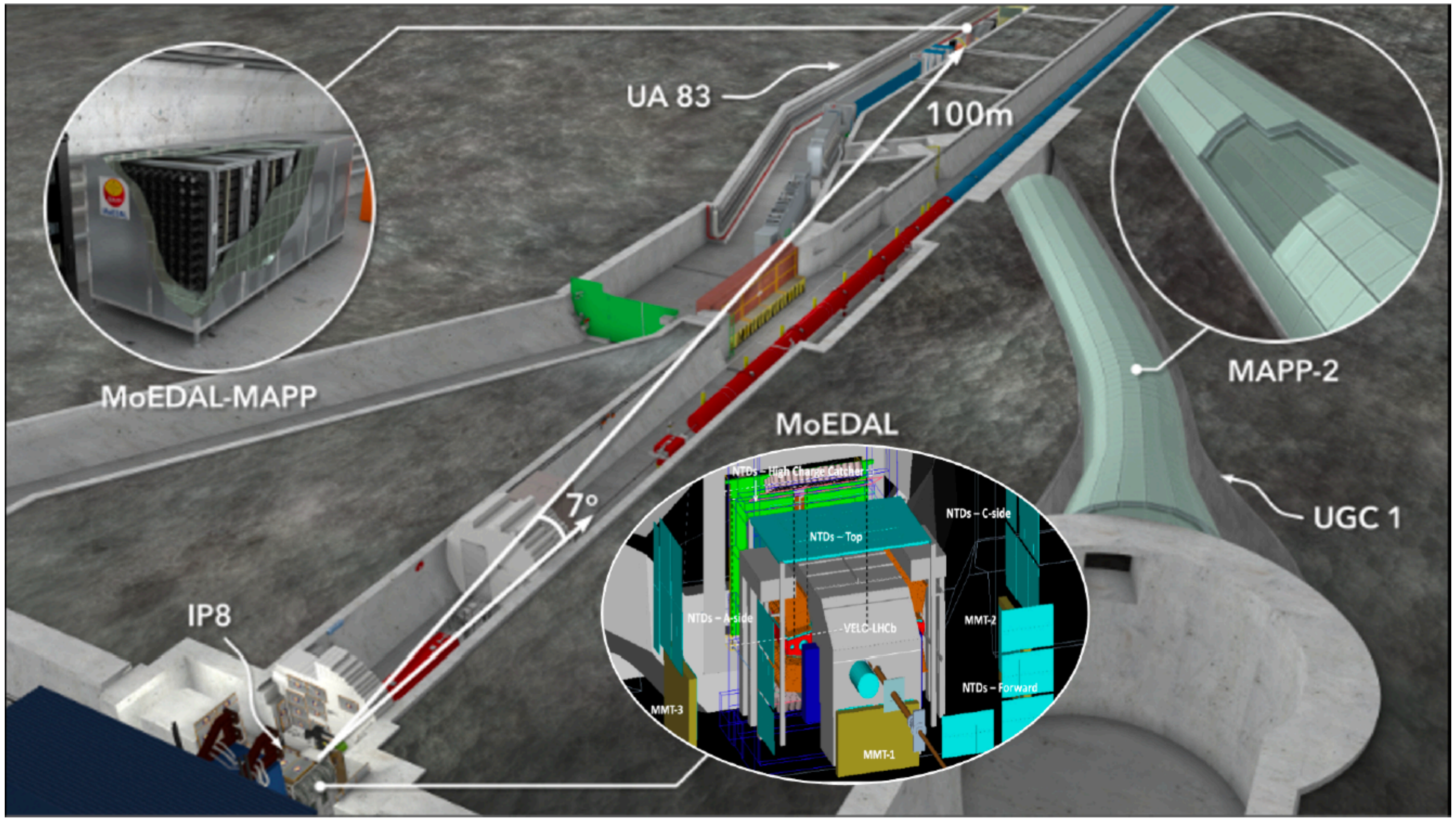
- miniCharged Particles (**mCPs**)
- Long-Lived electrically neutral Particles



Courtesy of V.Mitsou

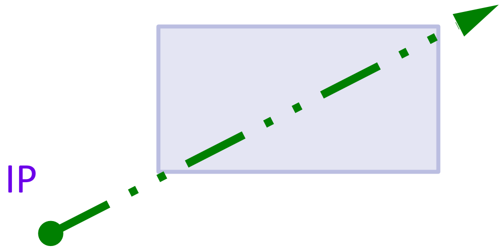
MoEDAL APPARATUS for PENETRATING PARTICLES

The installation of *MAPP* was unanimously approved by the LHCC in 2021



MAPP-1 for Run3 (*UA83 gallery*)

- sensitive to low ionisation induced by millicharged particles (charges $\ll 1e$)

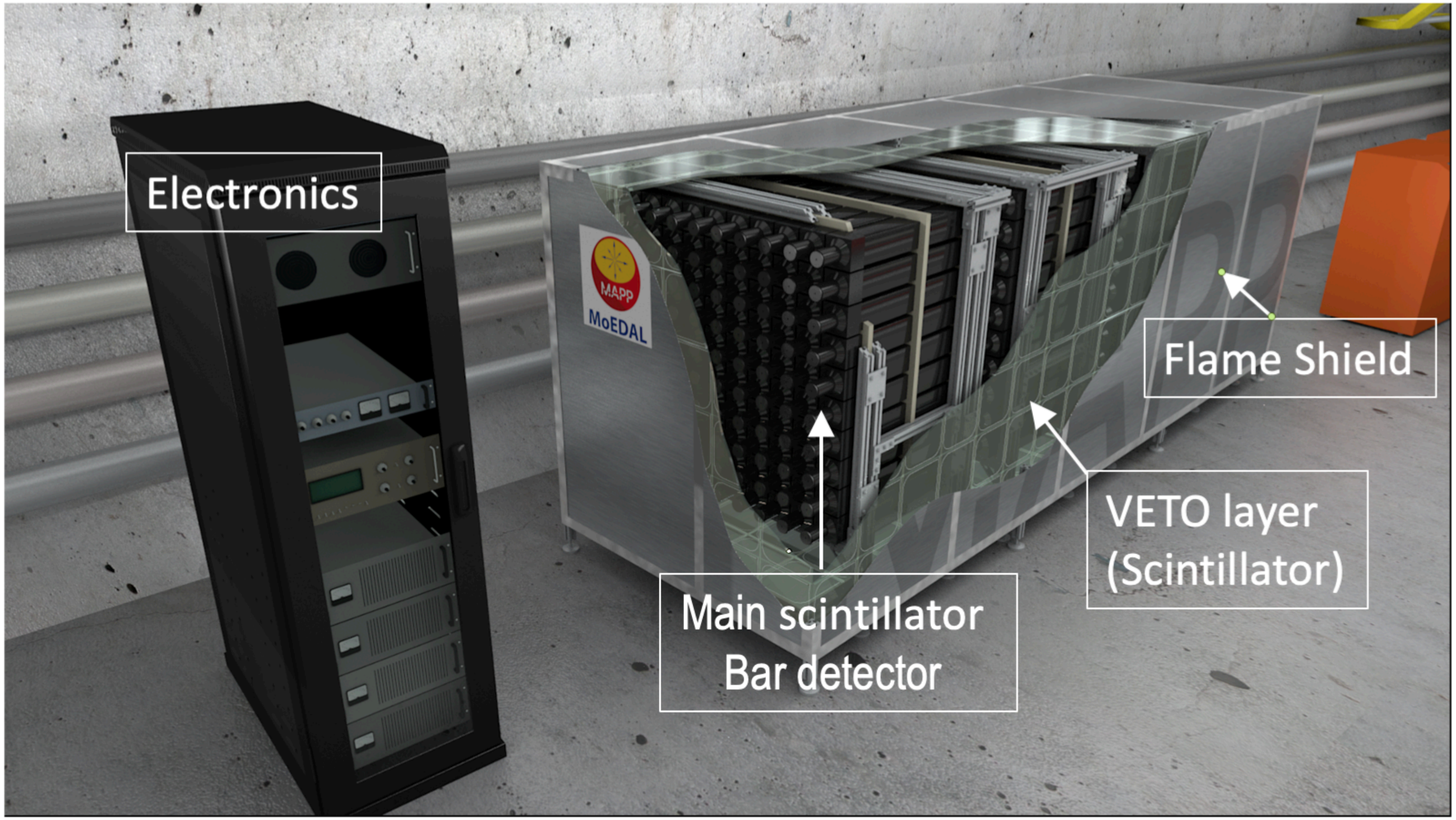


- At forward region w.r.t. beam axis
- Protected by ~100 m of rock overburden

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

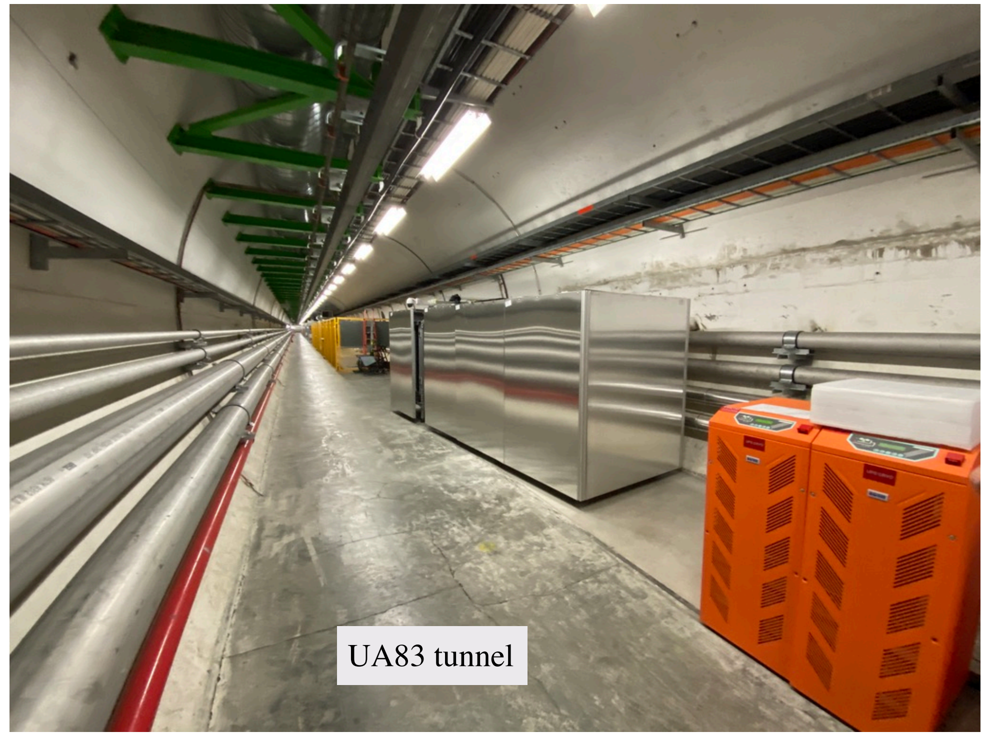
MoEDAL contribution to Snowmass, arXiv:2209.03988
Pinfold, Phil.Trans.Roy.Soc.Lond.A 377 (2019) 20190382

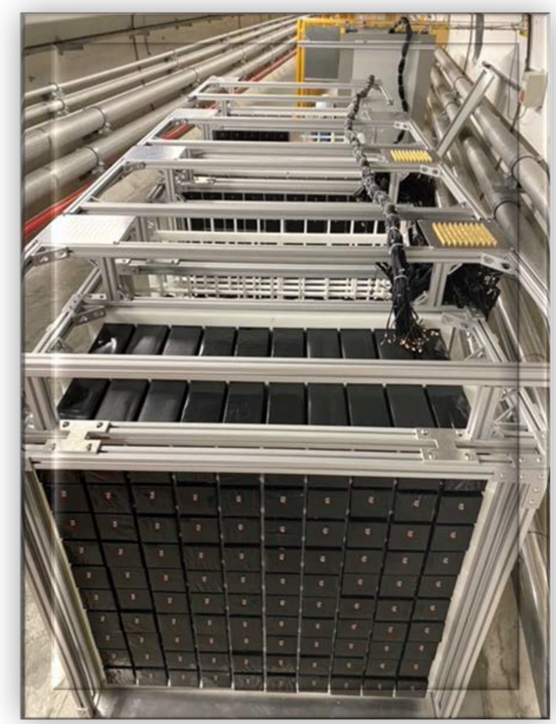
THE MAPP DETECTOR



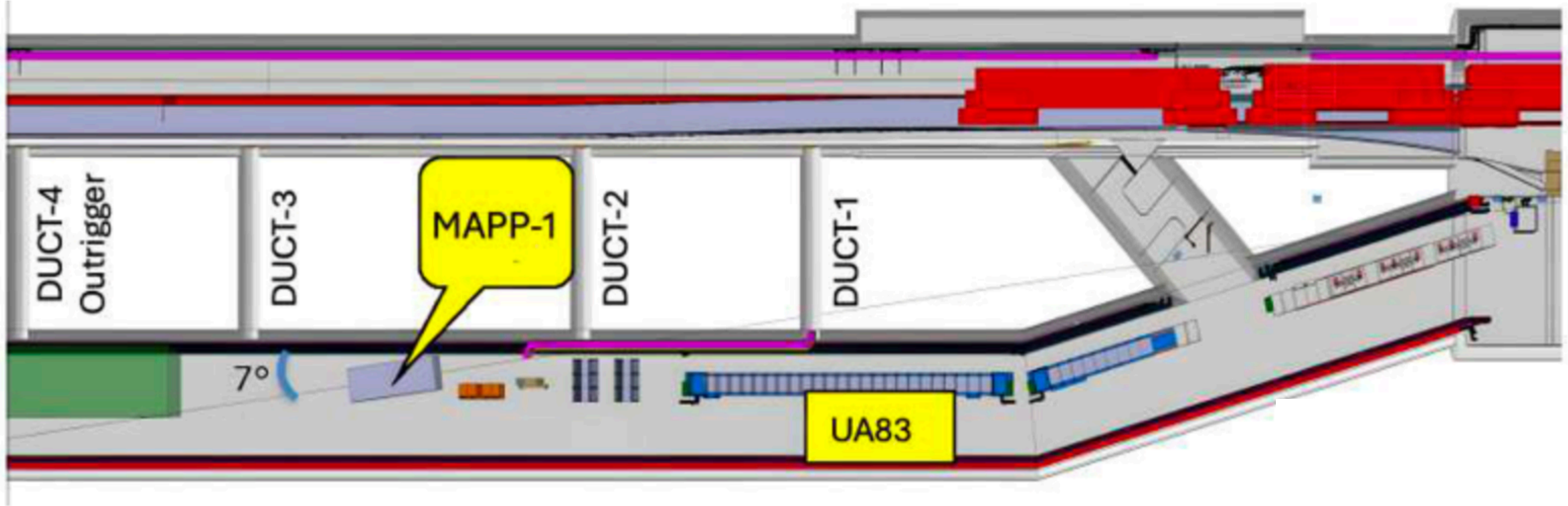
- 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
- Main support structure is comprised of generic T-bar extruded aluminium construction bars
- Bars protected by a hermetic VETO counter system
- MAPP detector and VETO layer are enclosed in an aluminium flame shield (1.3 m × 1.5 m × 4 m)

MAPP INSTALLATION

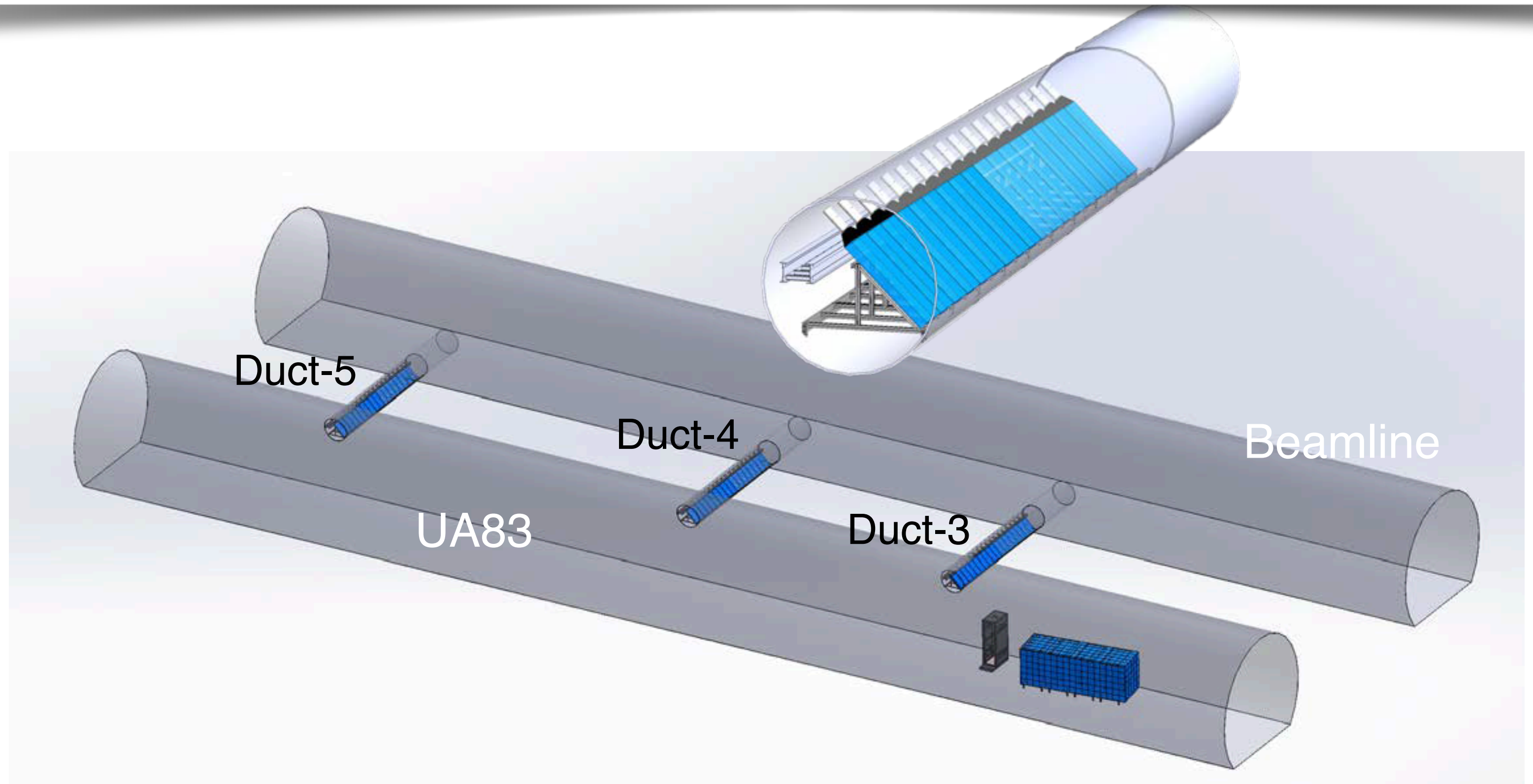


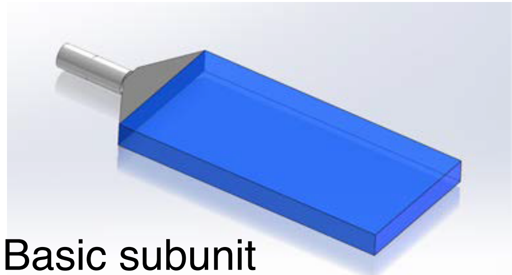


The MAPP-1 Outrigger Detector



- To increase the acceptance of MAPP-1 at higher mass and larger fractional charge (~ 0.01e)
- Size of the scintillator “planks” 60cm × 30cm × 5cm, inclined at 45º
- ~120 m from IP8; covers from ~2–6º
- Four-fold coincidence between the PMTs in each layer

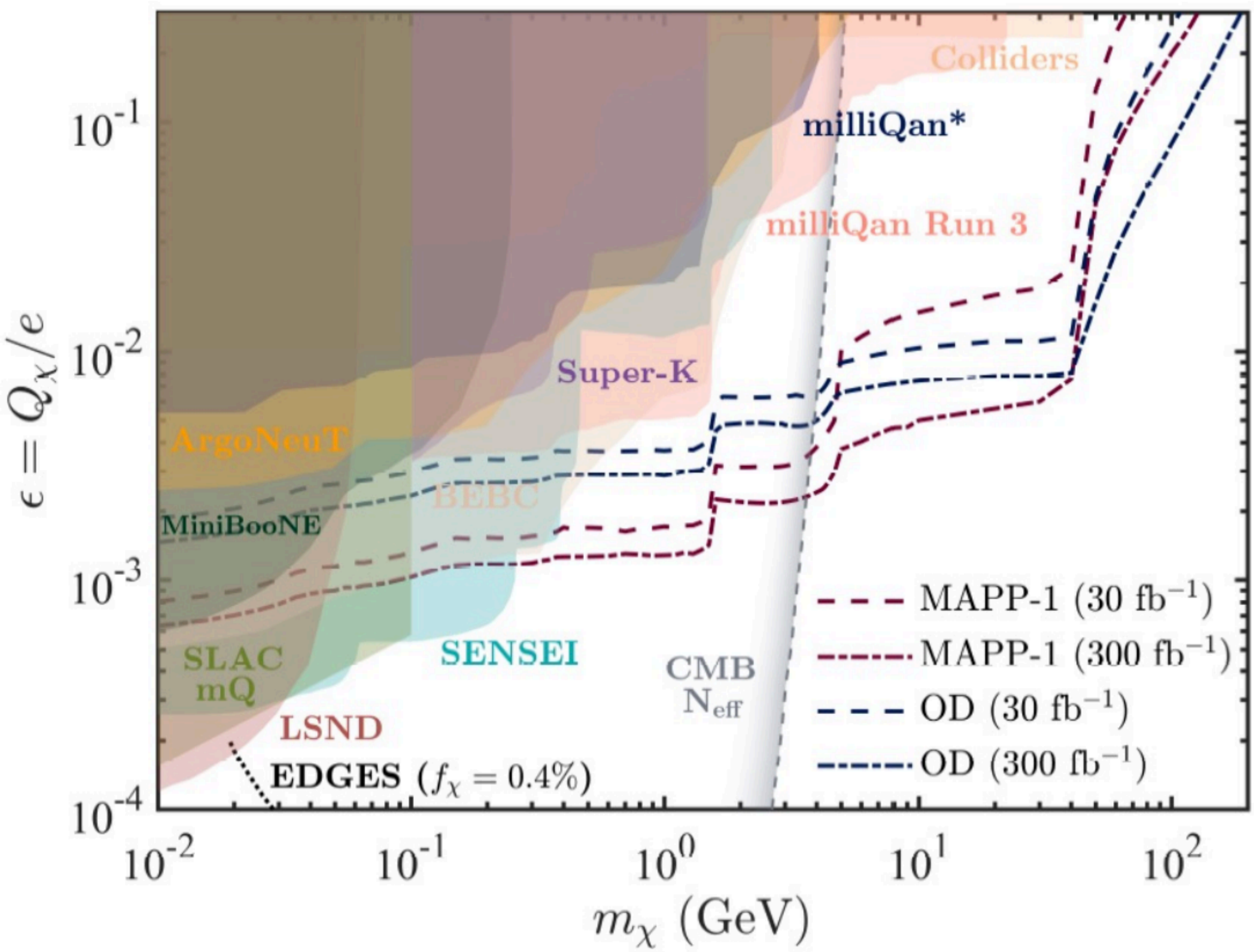


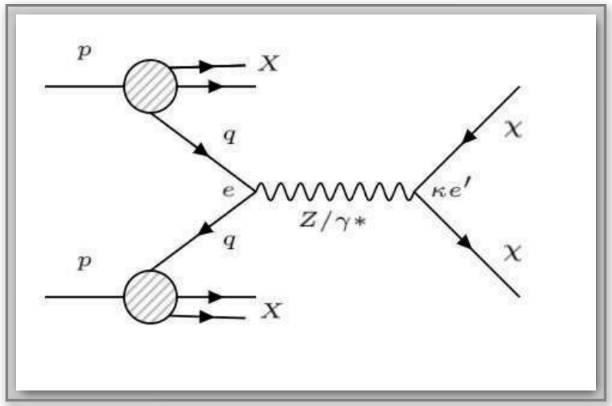


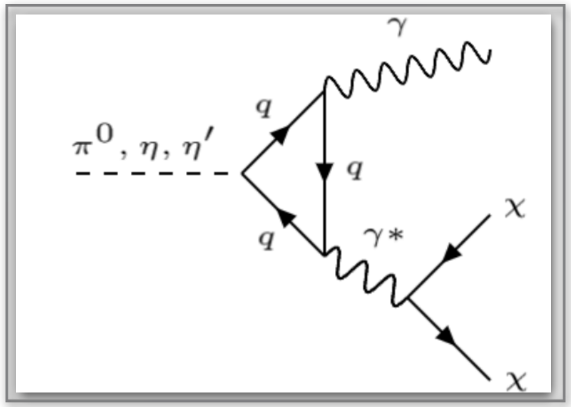
MoEDAL APPARATUS for PENETRATING PARTICLES

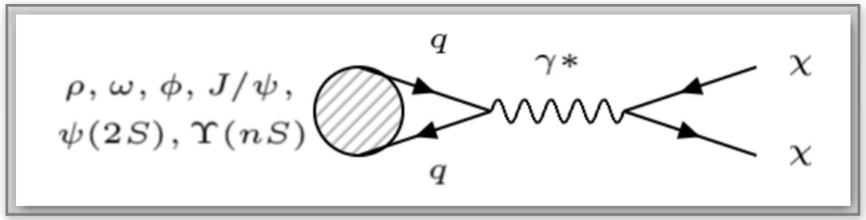
miniCharged Particles

- 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, Mitsou, Montigny, Mukhopadhyay, Ouimet, Pinfold, Shaa, Staelens, JHEP 04 (2024) 137 & arXiv:2508.04896 [hep-ph], EPJ-ST, to appear

Prospects for milli-charged dark pions: Arifeen, Ouimet, Pinfold, Staelens, arXiv:2509.02821 [hep-ph]

SUMMARY & OUTLOOK

➡ MoEDAL is one of the leaders in the search for HIPs at the LHC, provided pioneering results in the field (so far at least)

- sole contender in high magnetic charges & ultra-high electric charges
- sole dyon (electric & magnetic charge) search in accelerator experiments
- first search for monopoles produced via Schwinger mechanism

➡ Strong theory–experiment synergy within MoEDAL has inspired novel phenomenological work, from photon-fusion and Schwinger-production studies to advanced resummation approaches

➡Run-3 data taking underway; HL-LHC operation planned. MoEDAL keeps pushing the theory and experiment of Magnetic Monopoles and HECOs

➡ MAPP will extend MoEDAL's reach to mCPs and neutral LLPs, offering sensitivity competitive with other experiments.

Thanks for your attention!

Backup slides

Magnetic Monopoles

GUT monopole

G. 't Hooft, *Nucl. Phys. B79, 276* (1974),
A. M. Polyakov, *JETP Lett. 20, 194* (1974)

- 't Hooft and Polyakov showed that monopoles are fundamental solutions to non- Abelian gauge grand unification theories (GUTs)
- 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 colliders
- Size: **extended object**
  - radius > few femtometers

Electroweak Monopole

J.Ellis, N. Mavromatos, T.You, *Phys.Lett.B* 756 (2016) 29-35

- In 1986, Cho & Maison envisioned a spherically- symmetric EW monopole arising from the framework of the Weinberg-Salam model
- Non-trivial hybrid between the Dirac and the 't Hooft & Polyakov monopole
- Properties
  - charge $2g_D$
  - mass predicted to be ~4 -10 TeV

  ➜ accessible to LHC !

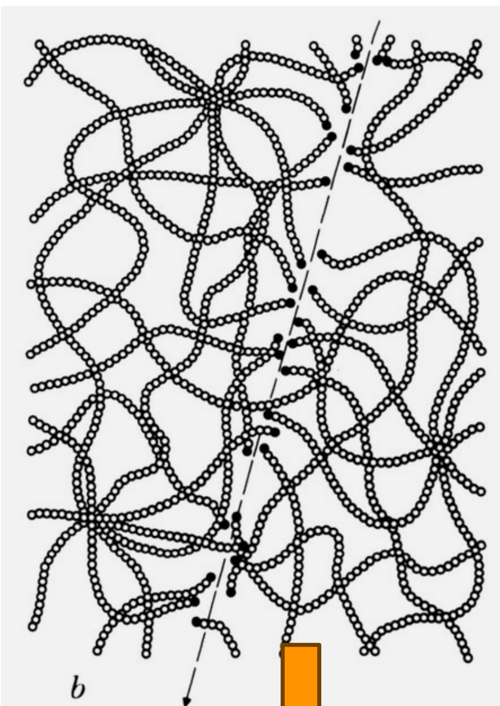
Monopolium

Epele, Fanchiotti et al., *EPJ Plus 127* (2012) 60

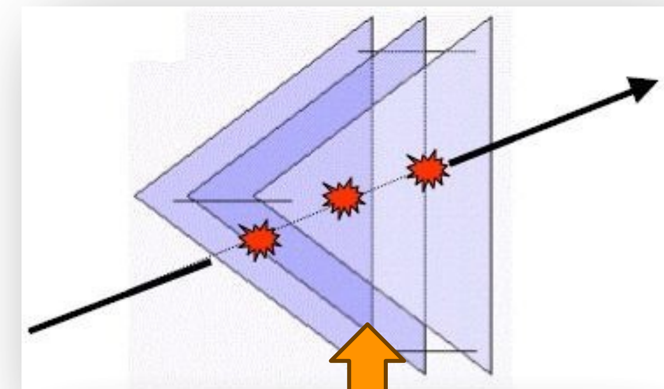
- Monopoles may not be free states but bound states → **monopolium**
- It can be detected via its decay to **two photon**

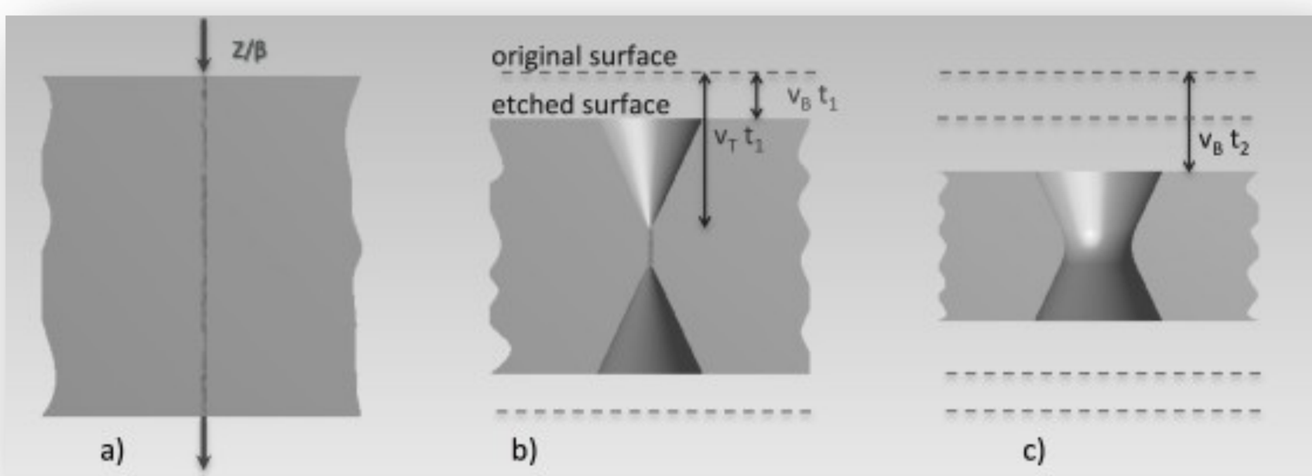
Nuclear Track Detectors (NTDs)

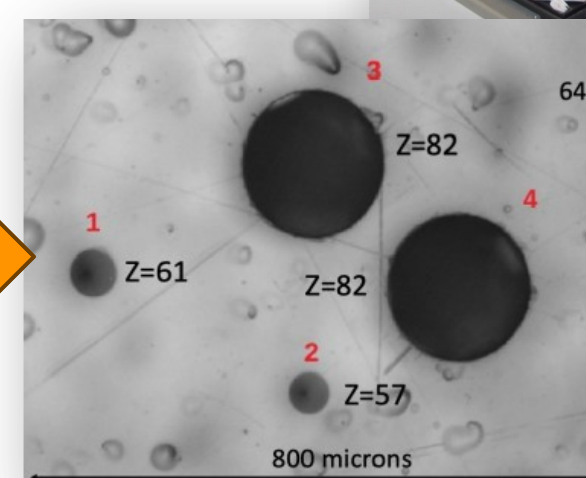
NTDs – plastic sheets made up of isotropic poly-allyl-diglycol carbonate polymer (CR39) or polycarbonate plastic such as Makrofol or Lexan.



- 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



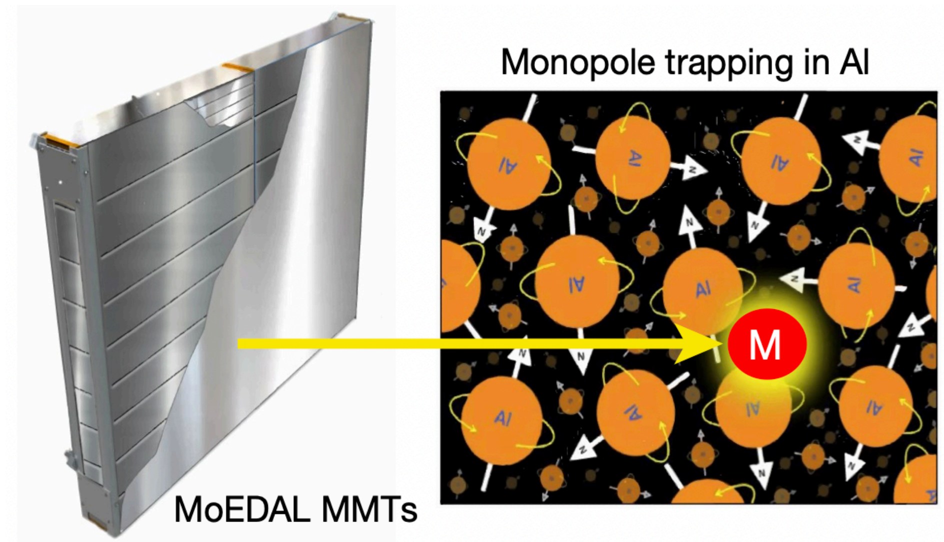


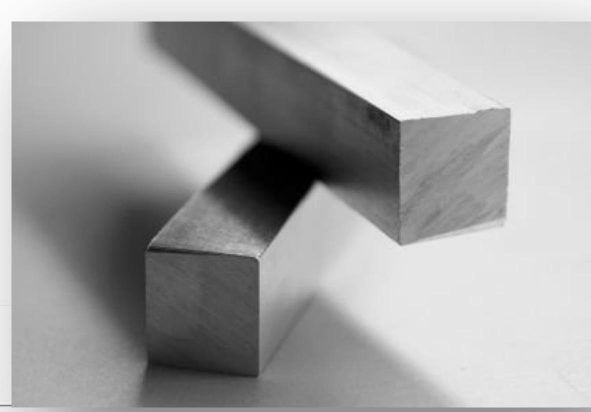


MMT: Magnetic Monopole Trapper

The trapping detector comprises ~ 800 kg of Aluminum bars

- Binding *(trapping)* of monopoles with nuclei and nucleons
- Al nuclei - large nuclear magnetic moment bind a magnetically-charged particle with an energy of 0.5-2.6 MeV - capture it inside the atomic lattice
- Aluminium MMT volumes scanned in superconducting quantum interference device (SQUID) magnometers at ETH Zurich
- MMT bars cut into pieces & fed into SQUID, several times
- **Persistent current:** difference between resulting current before and after scanning





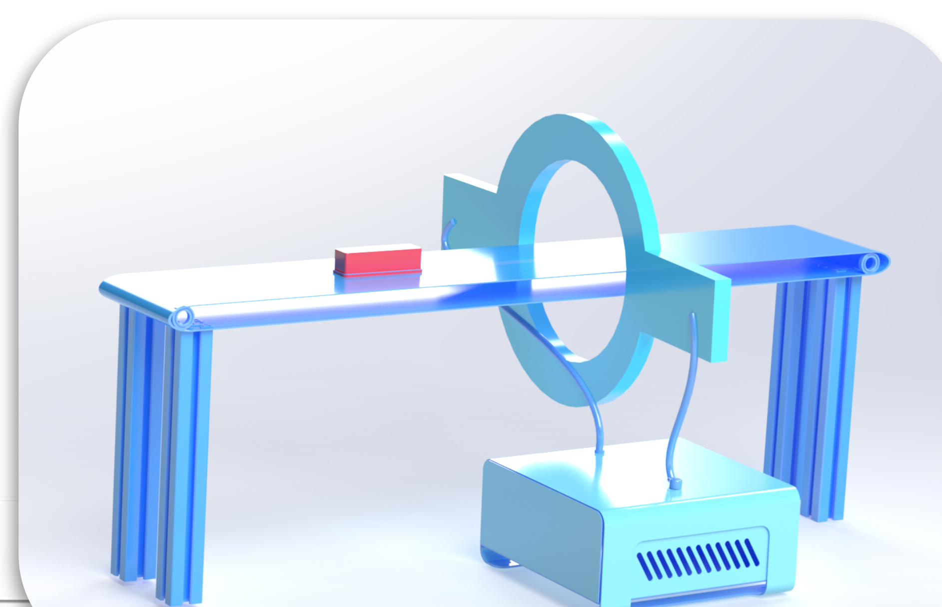
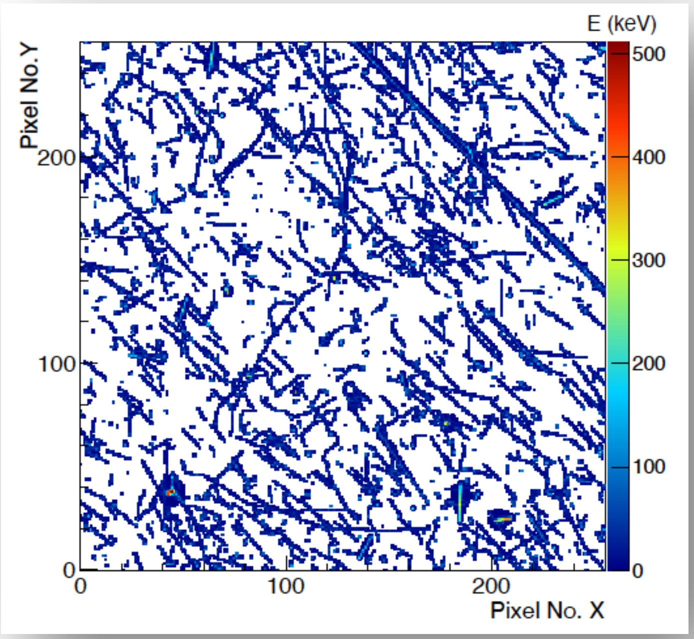


Illustration of a sample being passed through the SQUID.

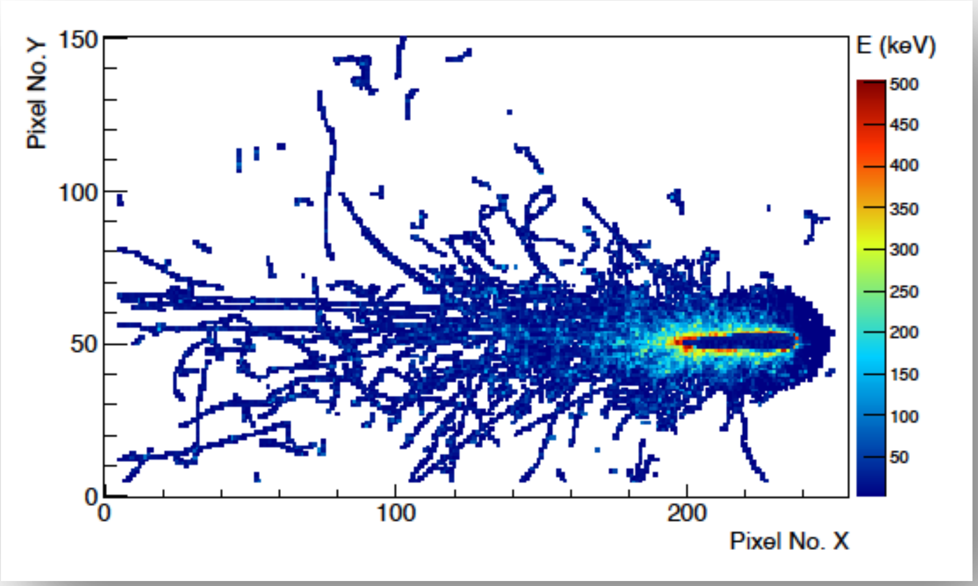
TimePix radiation monitor

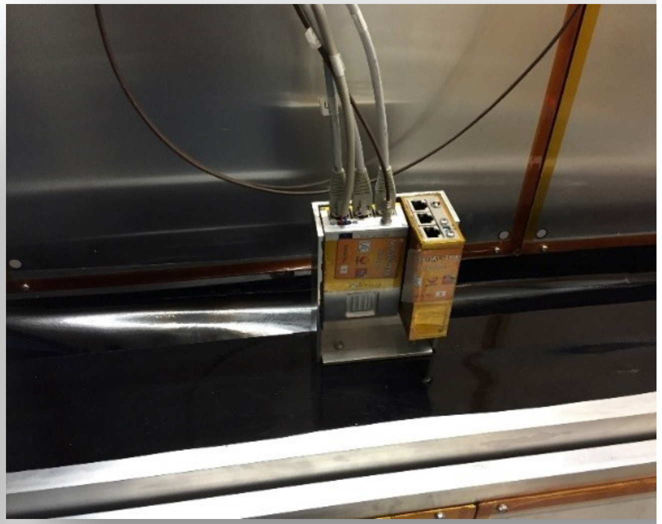
- Timepix chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic “bubble- chambers”
- **The only active element in MoEDAL**

- 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*



330 GeV Pb-ion measured at the SPS





MoEDAL, PoS ICHEP2020 (2021) 720

MAPP *PHYSICS PROGRAM* - *miniCharged Particles*

- Predicted by various theories beyond the Standard Model
- We consider class of FIPs that has a mill-charge as small as $10^{-3}e$ or lower
- mCPs connect naturally to the dark sector (via the vector portal/dark photon)

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{A}' + im_\chi)\chi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

U'(1) gauge field (*Dark Photon*)

Massive Dark Fermion

mixing term

$$A'_\mu \rightarrow A'_\mu + \kappa B_\mu$$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{A}' - i\kappa e'\not{B} + im_\chi)\chi$$

minicharge

Fractional charge $\epsilon = \dfrac{\kappa e' \cos\theta_W}{e}$

Holdom, B., *Phys. Lett. B* 166(2), 196–198 (1986)