Searching for New Physics with the MoEDAL Experiment at the LHC

Oscar Vives

On behalf of the MoEDAL-MAPP Collaboration

SUSY 2024

Theory meets Experiment

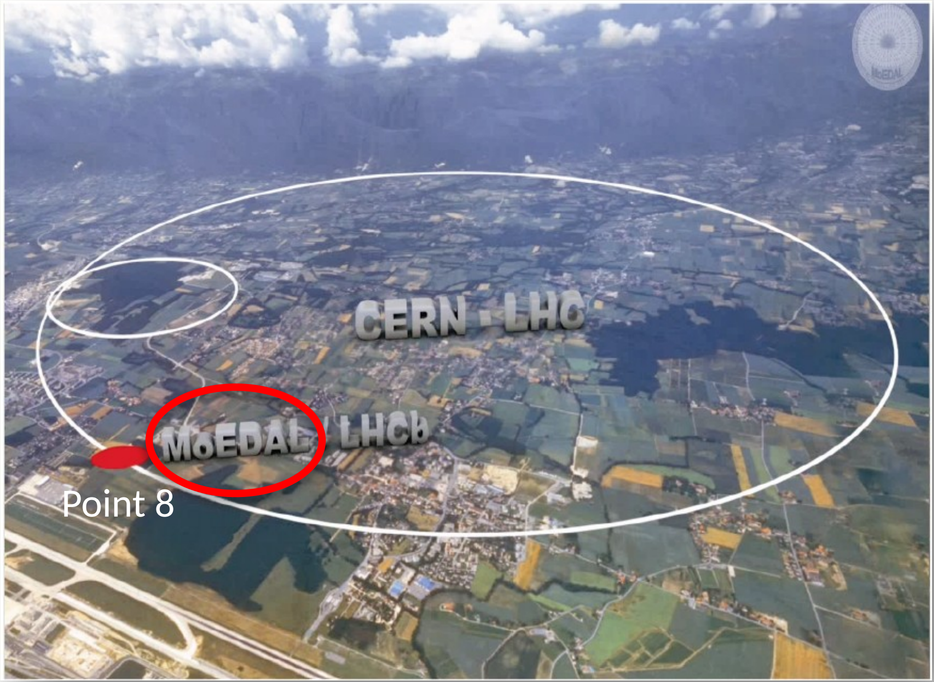
Madrid

10-14 June 2024

MAPP

MoEDAL

MoEDAL – Monopole & Exotics Detector At LHC



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
CENTER FOR QUANTUM SPACETIME, SEOUL
TUFT'S UNIVERSITY
IFIC VALENCIA
UNIVERSITY OF VIRGINIA

~60 physicists from 19 institutions

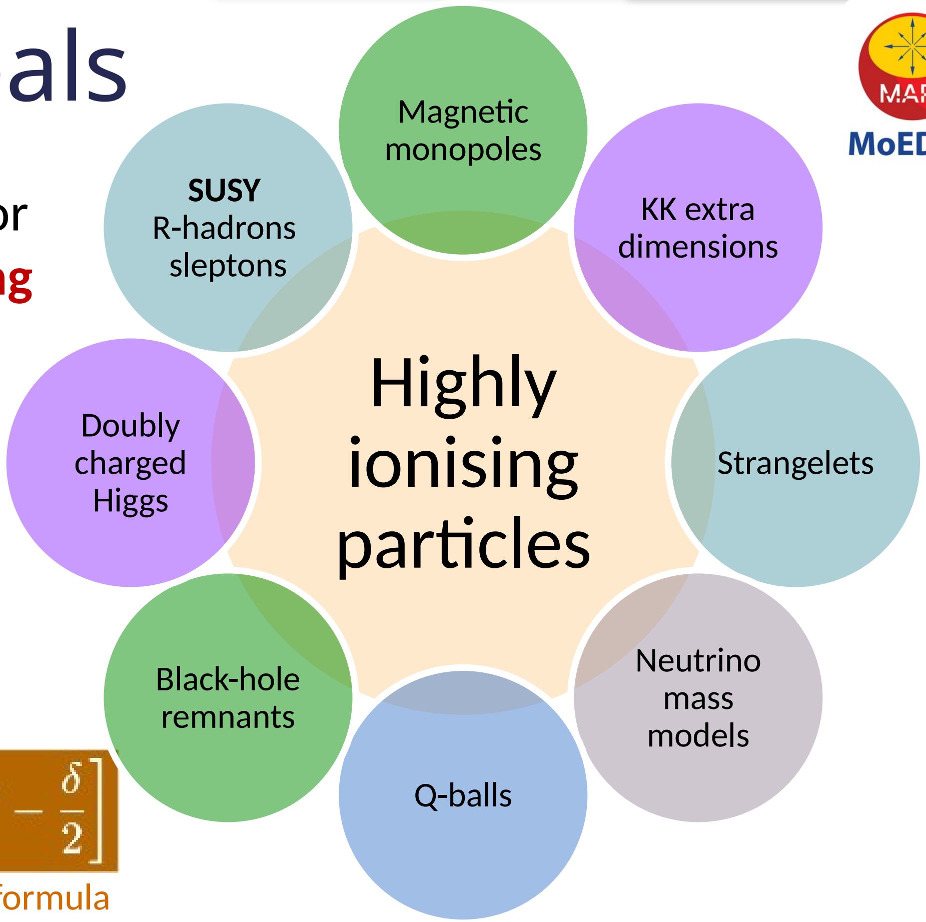
MoEDAL

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

MoEDAL physics goals

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



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

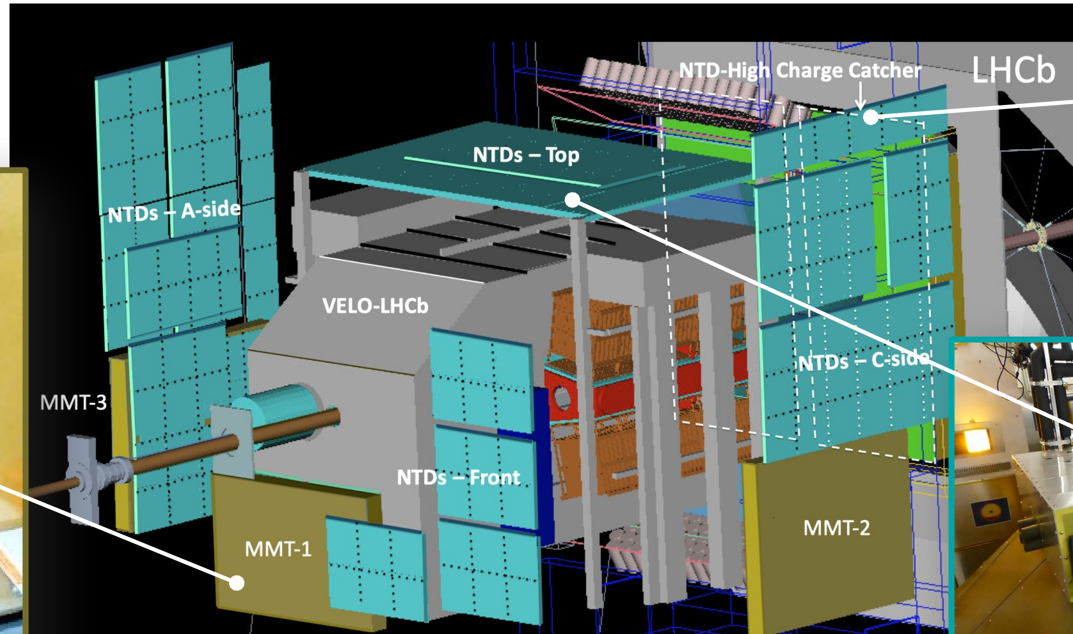
Bethe-Bloch formula

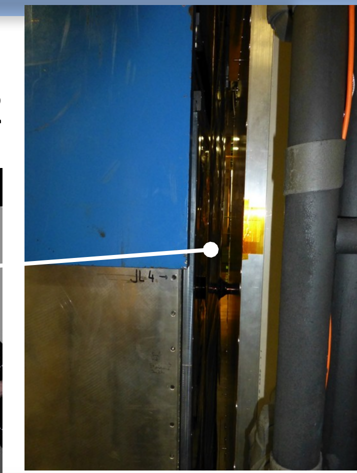
MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050

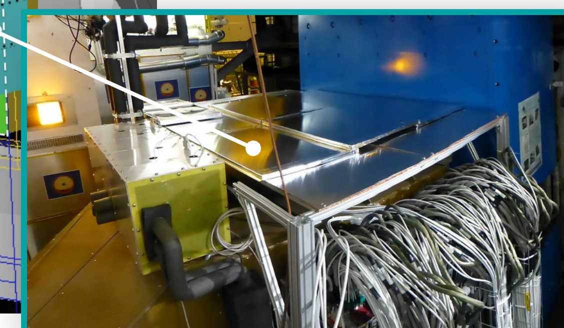
MoEDAL: the detector

Baseline MoEDAL detector

Run 2



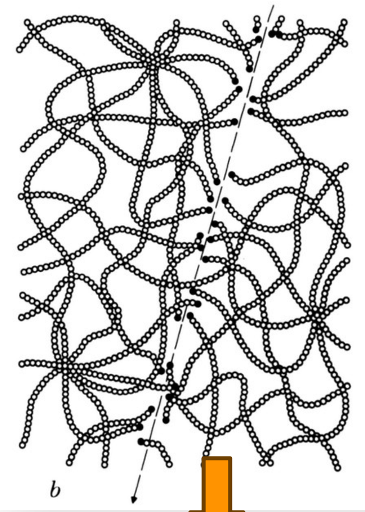




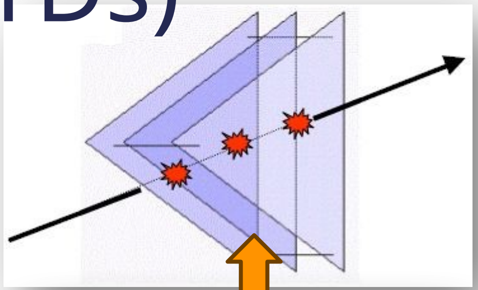
- Mostly **passive detectors**; no trigger; no readout
- Permanent physical record of new physics
- No Standard Model physics backgrounds

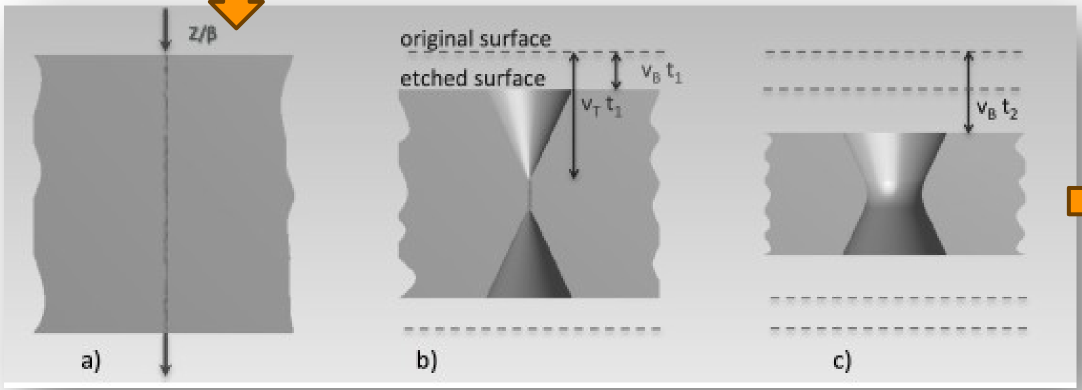
- Nuclear Track Detectors (**NTD**)
- Monopole Trapping detector (**MMT**) – aluminum bars
- **TimePix** radiation background monitor

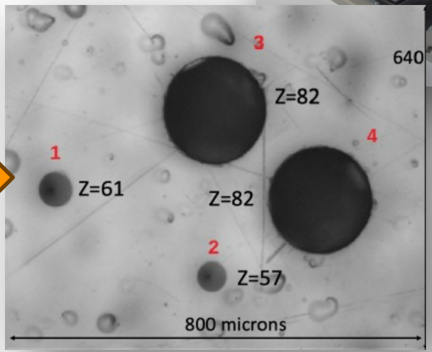
1️⃣ Nuclear Track Detectors (NTDs)



- 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

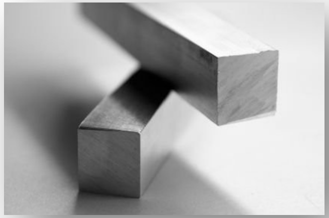


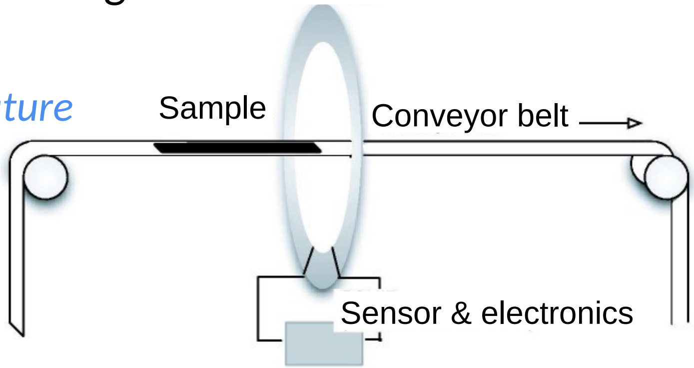




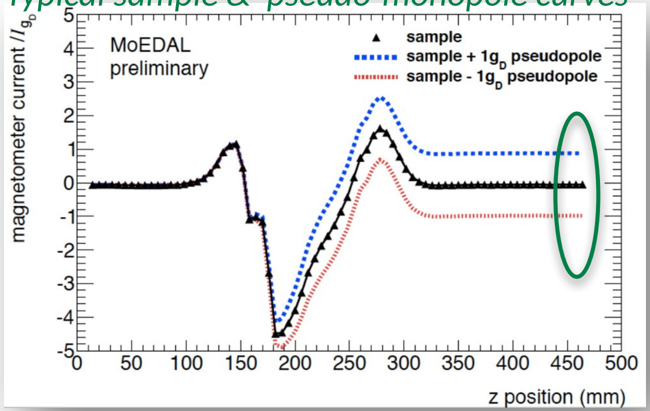
2 MMT: Magnetic Monopole Trapper

- 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 or more times
- **Persistent current:** difference between resulting current before and after scanning
  - other than zero
    → monopole signature





Typical sample & pseudo-monopole curves

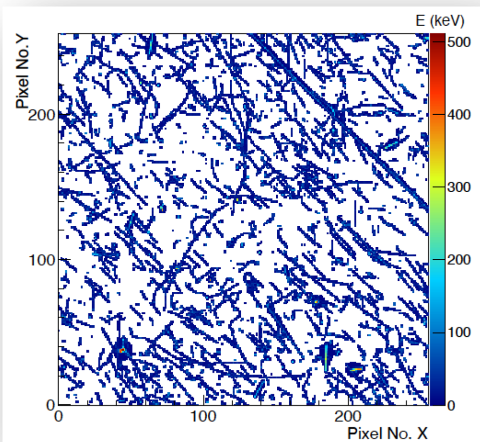


3 TimePix radiation monitor

MoEDAL

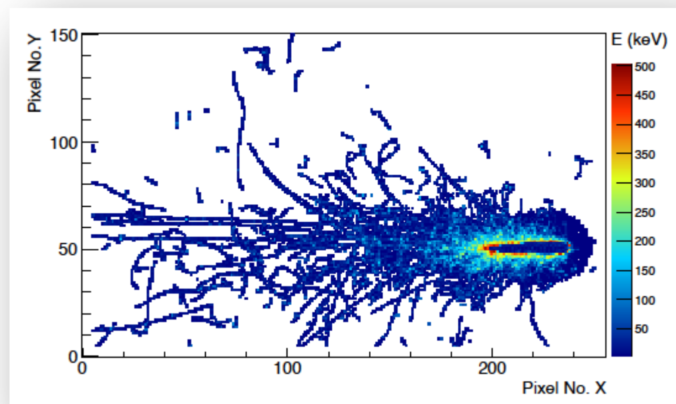
- Timepix chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic “bubble-chambers”
- **The only active element in MoEDAL**

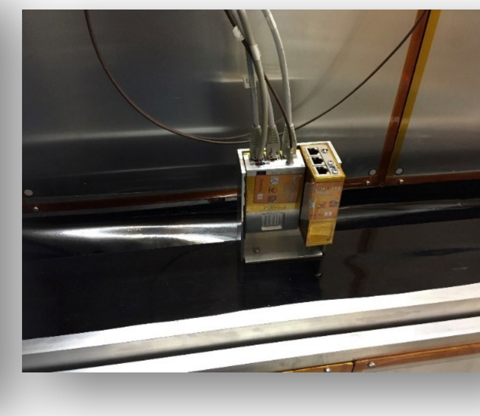
- 256×256 pixel with 55 µm pitch
- Time-of-interaction precision 1.56 ns
- 3D track reconstruction
- Energy deposition measured via time-over-threshold
- Particle ID through *dE/dx*



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

330 GeV Pb-ion measured at the SPS

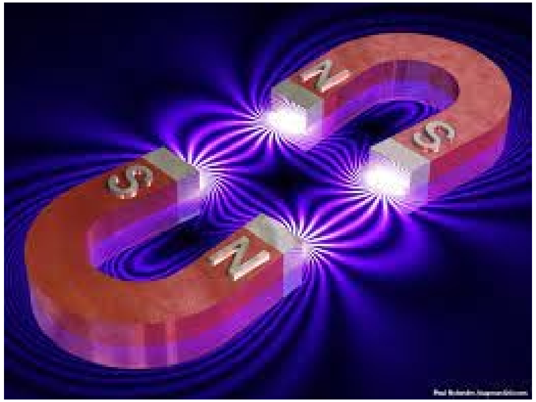




MoEDAL, [PoS ICHEP2020 (2021) 720]

Results on magnetic monopoles

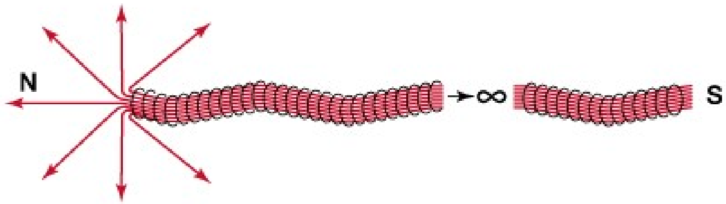
- Introduction to monopoles
- Summary of mass limits
- Dyons
- Schwinger production
- CMS beam pipe



Magnetic monopoles

- Symmetrise Maxwell's equations
  - electric ↔ magnetic charge duality
- **Paul Dirac** in 1931 hypothesised that magnetic monopole exists
  - monopole is the end of an infinitely long and infinitely thin solenoid (*Dirac's string*)
  - Dirac's quantisation condition:

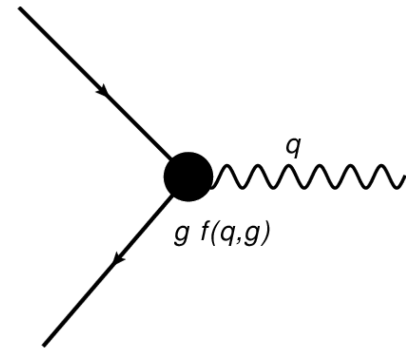
$$ge = n\left(\frac{\hbar c}{2}\right) \Rightarrow g = \frac{n}{2\alpha} e = n\, g_D = n\,(68.5\, e)$$



- In 1974 **'t Hooft and Polyakov** found that GUTs predict monopoles as topological solitons
  - produced in early Universe with mass 10^{17} – 10^{18} GeV
- **Yongmin Cho & Dieter Maison** proposed in 1986 the **electroweak monopole**
  - non-trivial hybrid between (Abelian) Dirac and (non-Abelian) 't Hooft-Polyakov monopoles
  - magnetic charge $2g_D$
  - mass between 4 to 7 TeV ⇨ **detectable at LHC!**

Review on monopole theory & searches:
Mavromatos & Mitsou, Int.J.Mod.Phys.A 35 (2020) 2030012

Monopole properties in a nutshell



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

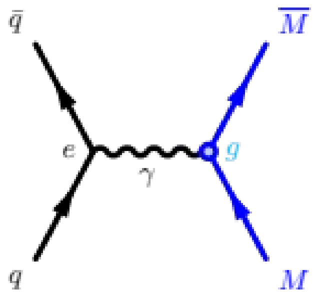
$$\vec{F} = g\left(\vec{B} - \vec{v} \times \vec{E}\right)$$

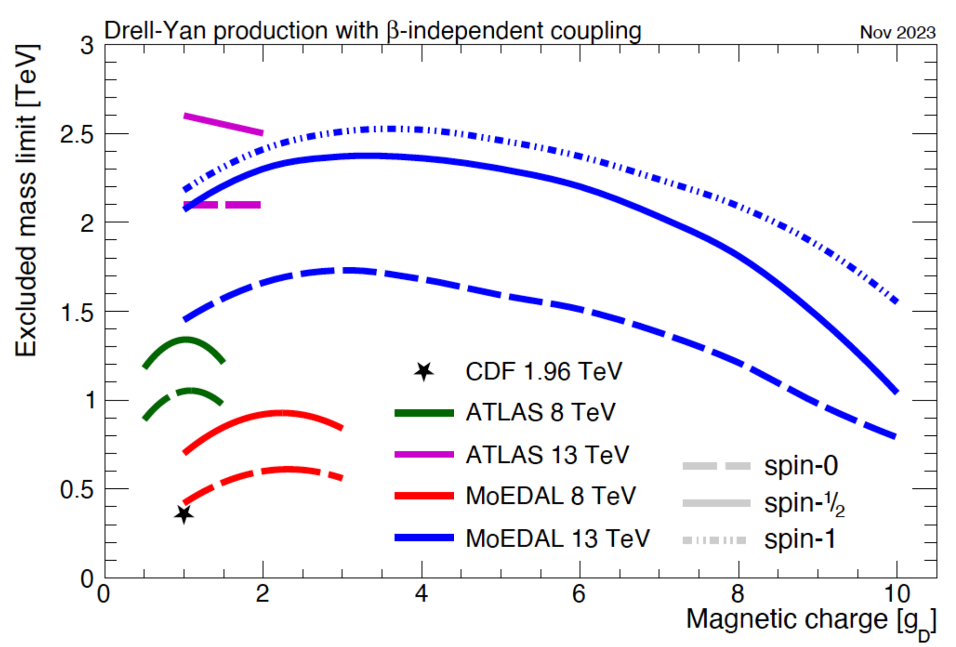
- Dirac monopole is a point-like particle; GUT monopoles are extended objects
  - production of composite monopoles exponentially suppressed by $e^{-4/\alpha}$
- Monopole spin and mass not determined by theory → free parameters

Magnetic monopole limits

MoEDAL

- Novelties in monopole models considered w.r.t. other experiments
  - β-dependent coupling
  - spin-1 monopoles
  - γγ fusión
- **ATLAS ↔ MoEDAL complementarity**



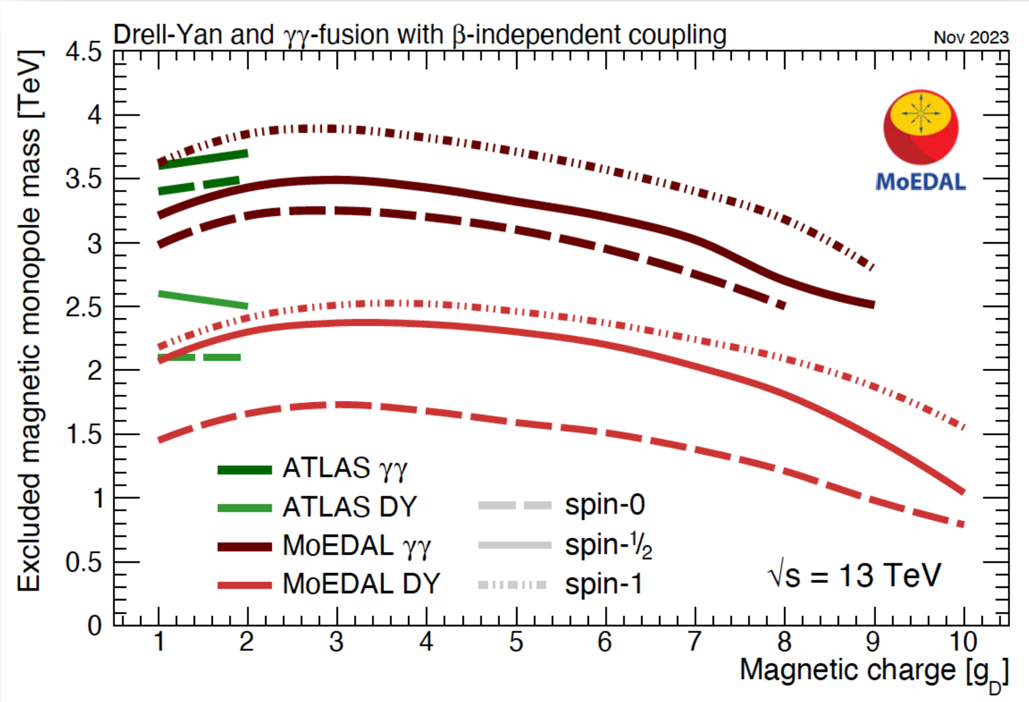


MoEDAL set world-best collider limits for |g| > 2 g_D

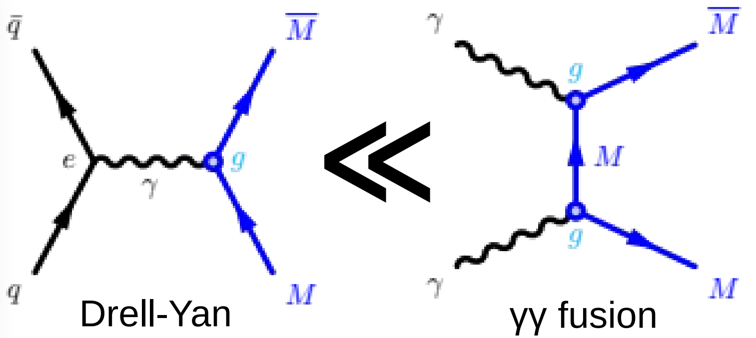
Mass limits extracted with Feynman-*like* diagrams that ignore **non-perturbativity** of **large monopole-photon coupling**. They serve as benchmarks to facilitate comparisons.

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

Drell-Yan & **γγ-fusion**



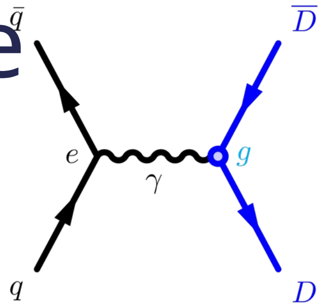
MoEDAL, Phys.Rev.Lett. 123 (2019) 021802,
Eur.Phys.J.C 82 (2022) 694, arXiv:2311.06509 [hep-ex]



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

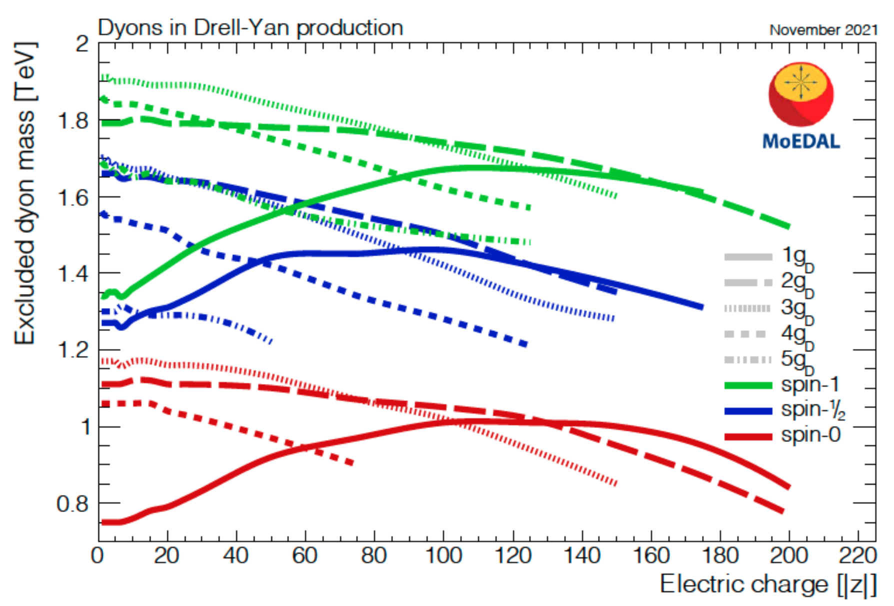
Baines, Mavromatos, Mitsou, Pinfold, Santra,
Eur.Phys.J.C 78 (2018) 966

Dyons: electric & magnetic charge



First explicit accelerator search for direct dyon production!

- 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

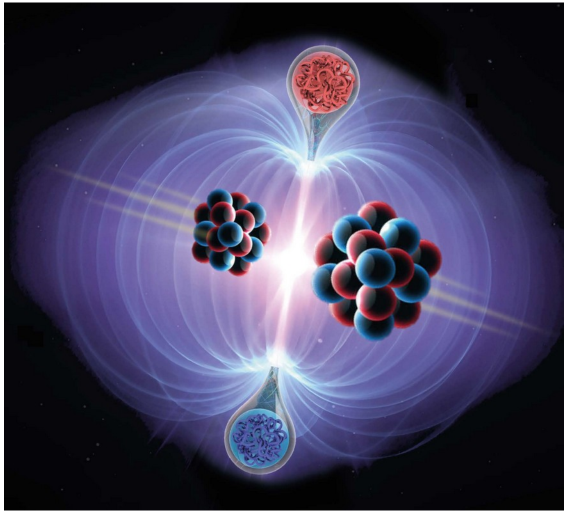


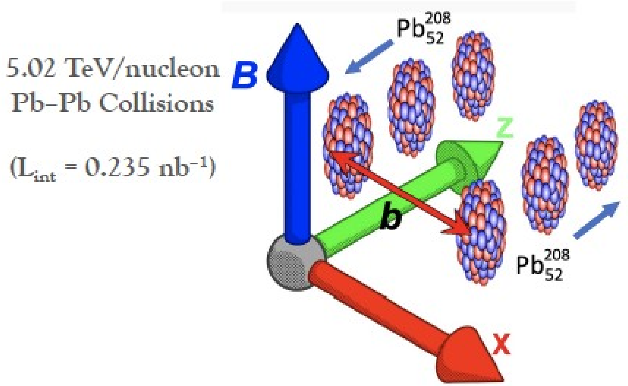
MoEDAL, Phys.Rev.Lett. 126 (2021) 071801

Monopoles via Schwinger mechanism

MoEDAL

- 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**
- Advantages over DY & γγ-fusion production
  - cross-section calculated with semiclassical techniques
  - no exponential suppression e^{-500} for finite-sized monopoles
- Exposure of MMTs in Pb-Pb collisions
  - peak magnetic field strength 10^{16} T
  - four orders of magnitude greater than strongest known astrophysical magnetic fields: surfaces of magnetars





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

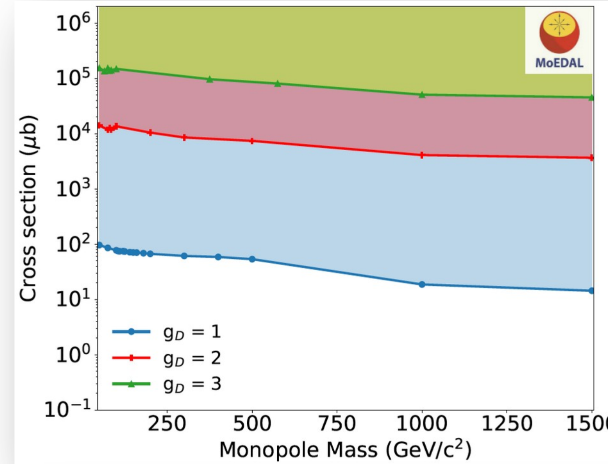
MoEDAL bags a first

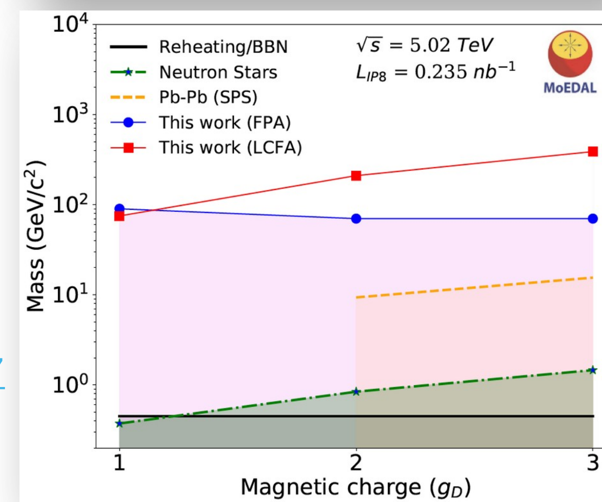
The MoEDAL experiment has conducted the first search at a particle collider for magnetic monopoles produced through the Schwinger mechanism

2 JULY, 2021 | By Ana Lopes

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

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



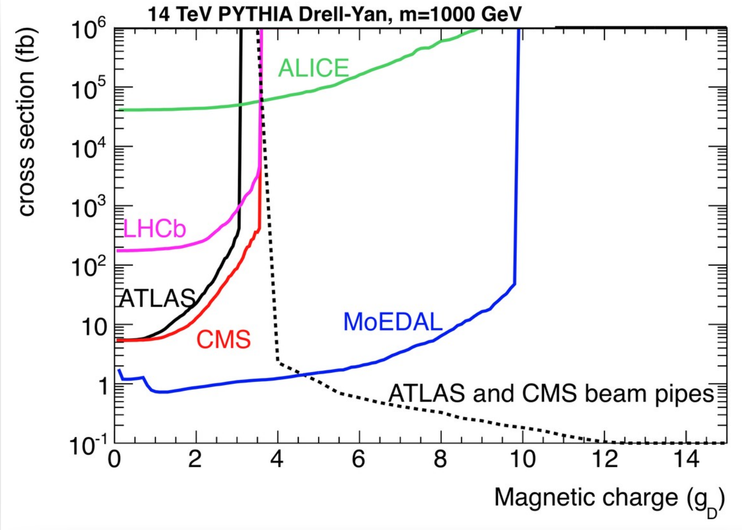


NEW

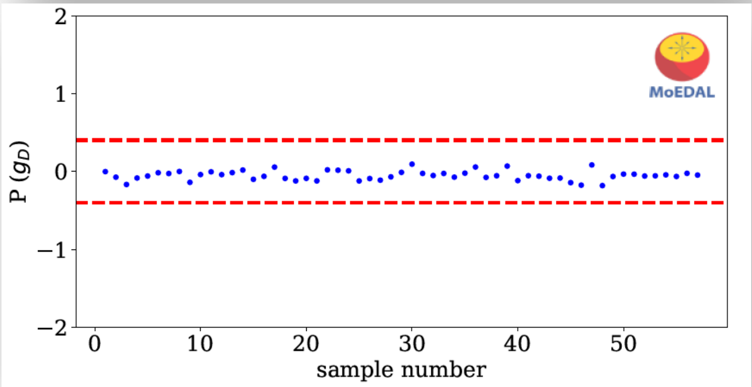
CMS Run-1 beam pipe

- Beam pipes
  - most directly exposed piece of material
  - cover very high magnetic charges
- **2012:** first pieces of CMS beam pipe tested [EPJC72 (2012) 2212]; far from collision point
- **2019:** CMS officially transfers ownership of Run-1 beam pipe to MoEDAL
  - 1 mm thick and 3.8 m long made of beryllium
- Scanned for presence of trapped magnetic monopoles by MoEDAL Collaboration with SQUID at ETH Zurich
- No statistically significant signal was observed

MoEDAL



De Roeck et al, EPJC72 (2012) 1985

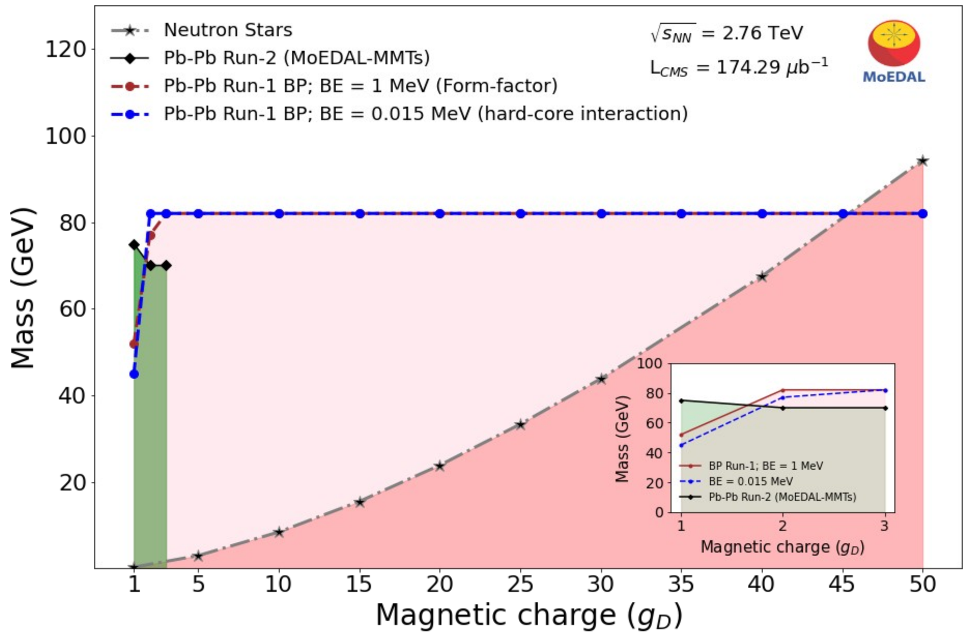


MoEDAL search in the CMS beam pipe for magnetic monopoles produced via the Schwinger effect, arXiv:2402.15682

Schwinger production & CMS beam pipe

- Monopole binding energy to a single proton in beryllium
  - 15.1 keV (conservative)
  - 1 MeV, if proton form factor taken into account
- Monopole kinetic energy sufficiently low to allow binding only when moving against magnetic field and “turns” inside beam pipe
- Composite or point-like monopoles with masses up to 80 GeV excluded

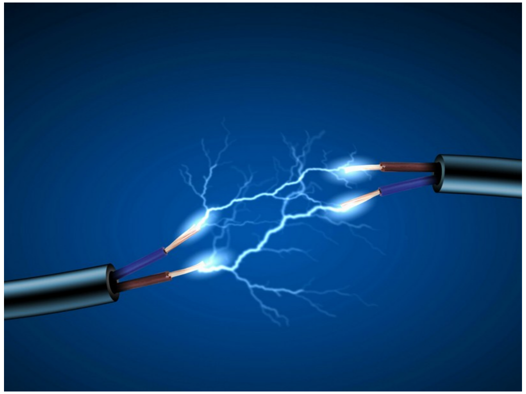
Strongest available constraint for magnetic charges 2 – 45 g_D



MoEDAL search in the CMS beam pipe for magnetic monopoles produced via the Schwinger effect, arXiv:2402.15682

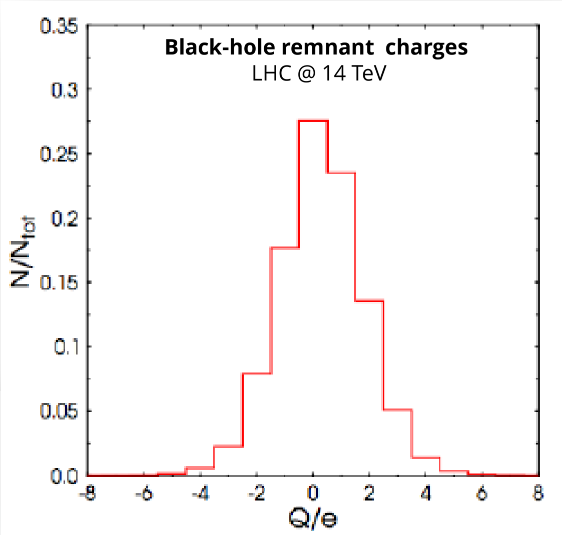
Electrically charged particles

- Run 1 & 2 results on HECOs (and monopoles)
- Prospects for low charges (1*e* – 4*e*)

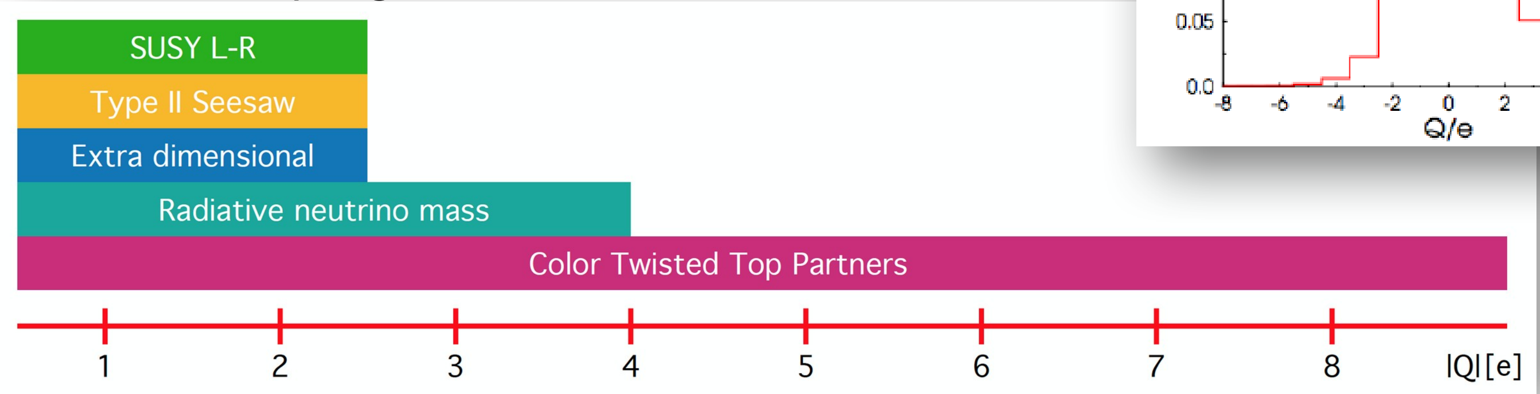


Multiply charged quasi-stable particles

- Highly Electrically Charged Objects (HECOs) predicted in many scenarios of physics beyond the SM
  - composite 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



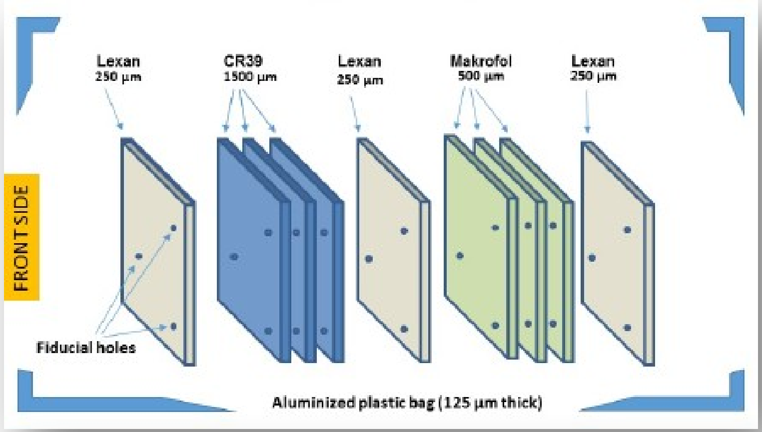
R. Masełek, DISCRETE2020-2021

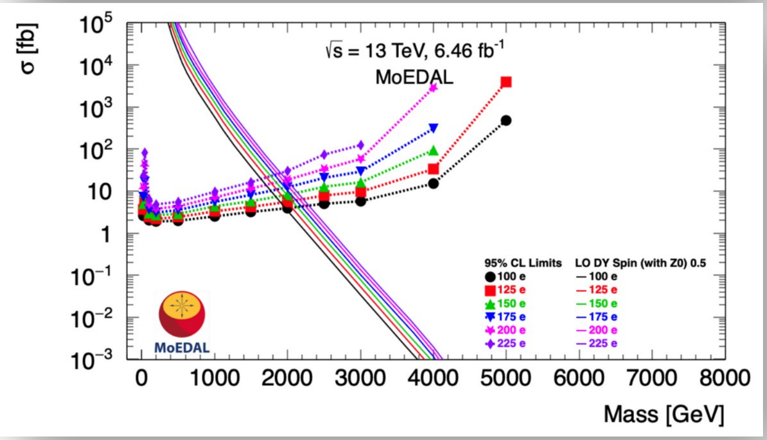
NTD+MMT search for HECOs & monopoles

MoEDAL

- First analysis on full NTD+MMT detectors
  - 10.7 m² low-threshold NTD + 3.24 m² High Charge Catcher
  - 800 kg aluminium MMT
- No HECO or monopole candidate tracks found in NTD scanning after etching
- No monopole candidates found in MMT SQUID análisis
- First MoEDAL analysis considering HECO production via photon fusion

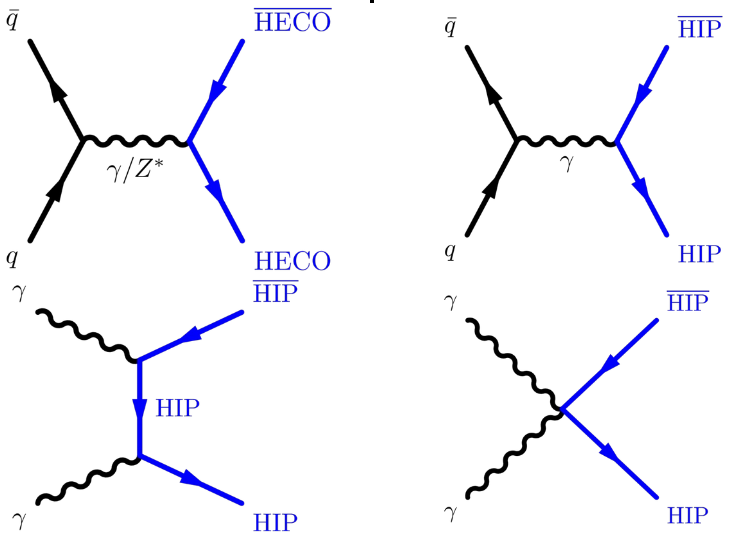
MoEDAL, arXiv:2311.06509 [hep-ex]



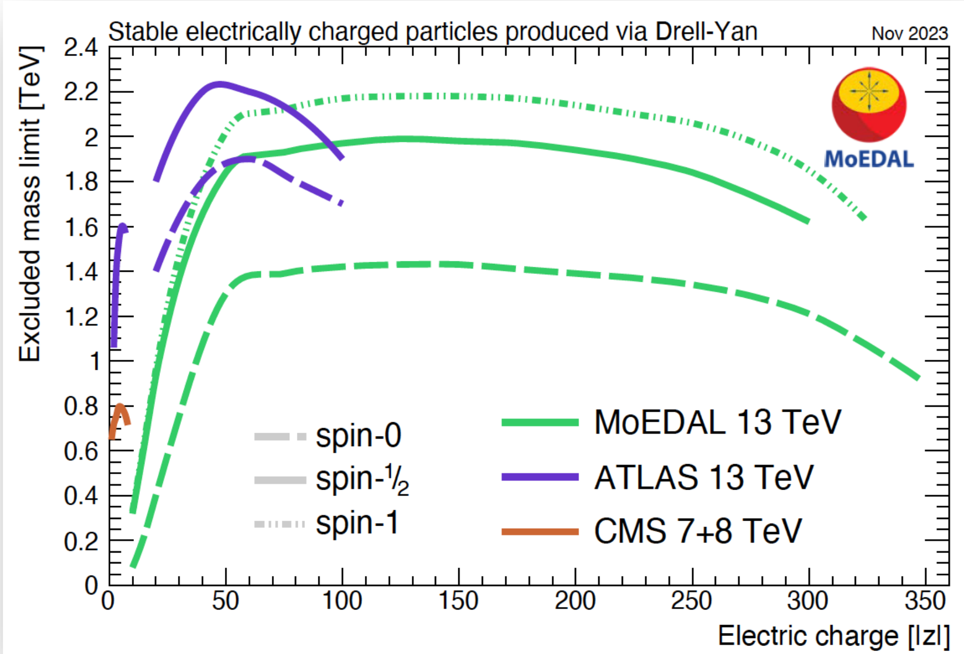


HECO limits

- Upper limits on production cross section as low as **1 fb**
- Limits on HECOs with electric charges **5*e* – 350*e*** and masses up to **~3.3 TeV**



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

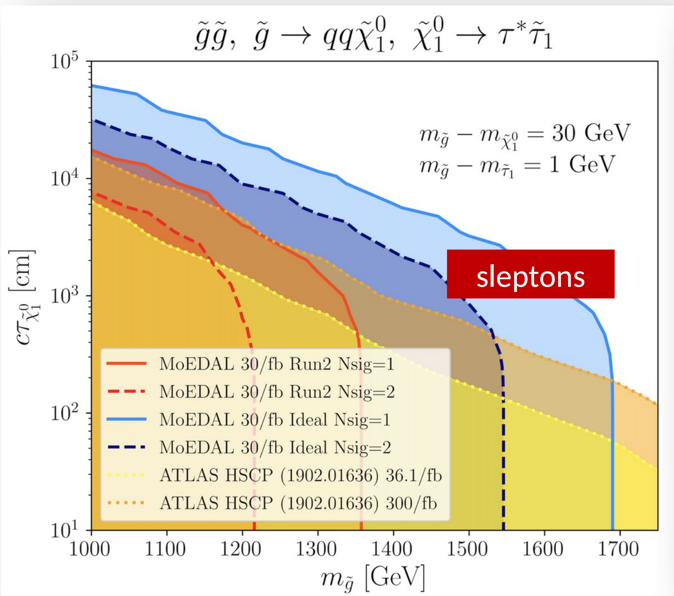


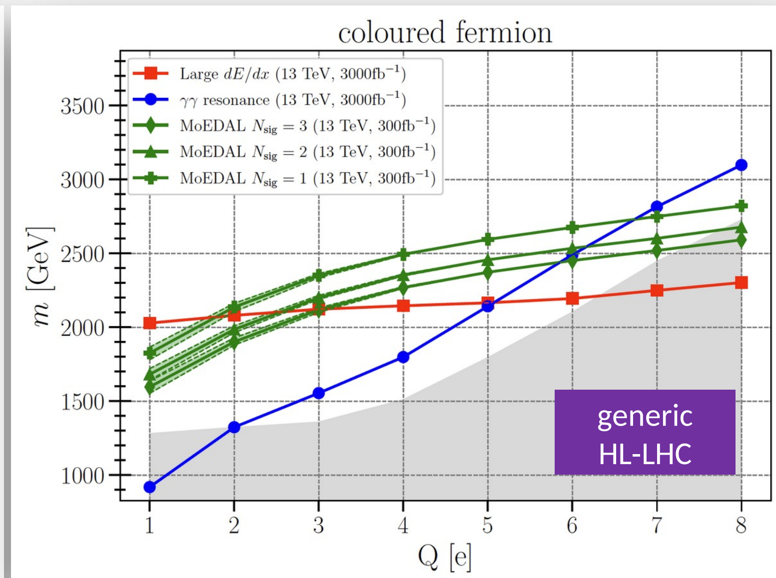
MoEDAL HECOs limits strongest to date, in terms of charge, at any collider experiment

Large photon-HIP coupling ⇒ perturbation th. breakdown ⇒ resummation. *E. Musemici, next talk.*

Prospects for “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]





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

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

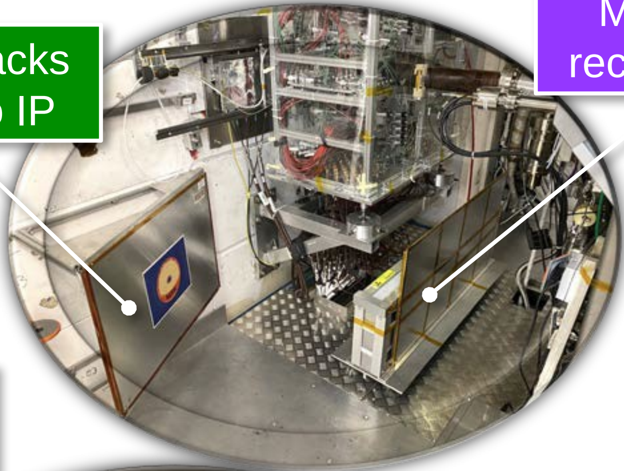
Altakach, Lamba, Masełek, Mitsou, Sakurai, EPJC 82 (2022) 848

Upgraded MoEDAL installed for Run-3

- Upgrades w.r.t. Run-2 MoEDAL
- Exposed to 2023 collisions
- Removed end of 2023 to allow for LHCb beampipe reworks
- Re-installed in Feb 2024

NTD stacks point to IP

Forward MMT box reconfigured



VELO-top NTD array installed

TimePix3 chips connected to LHC clock

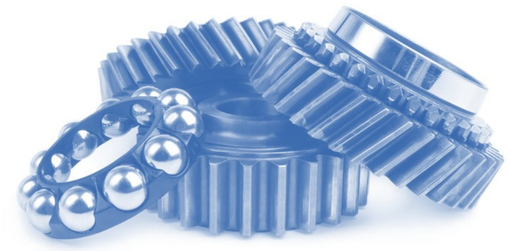
Summary & outlook

- 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**

See also E. Musemici talk on MAPP   MoEDAL web page: https://moedal.web.cern.ch/

Thank you for your attention!

Spares

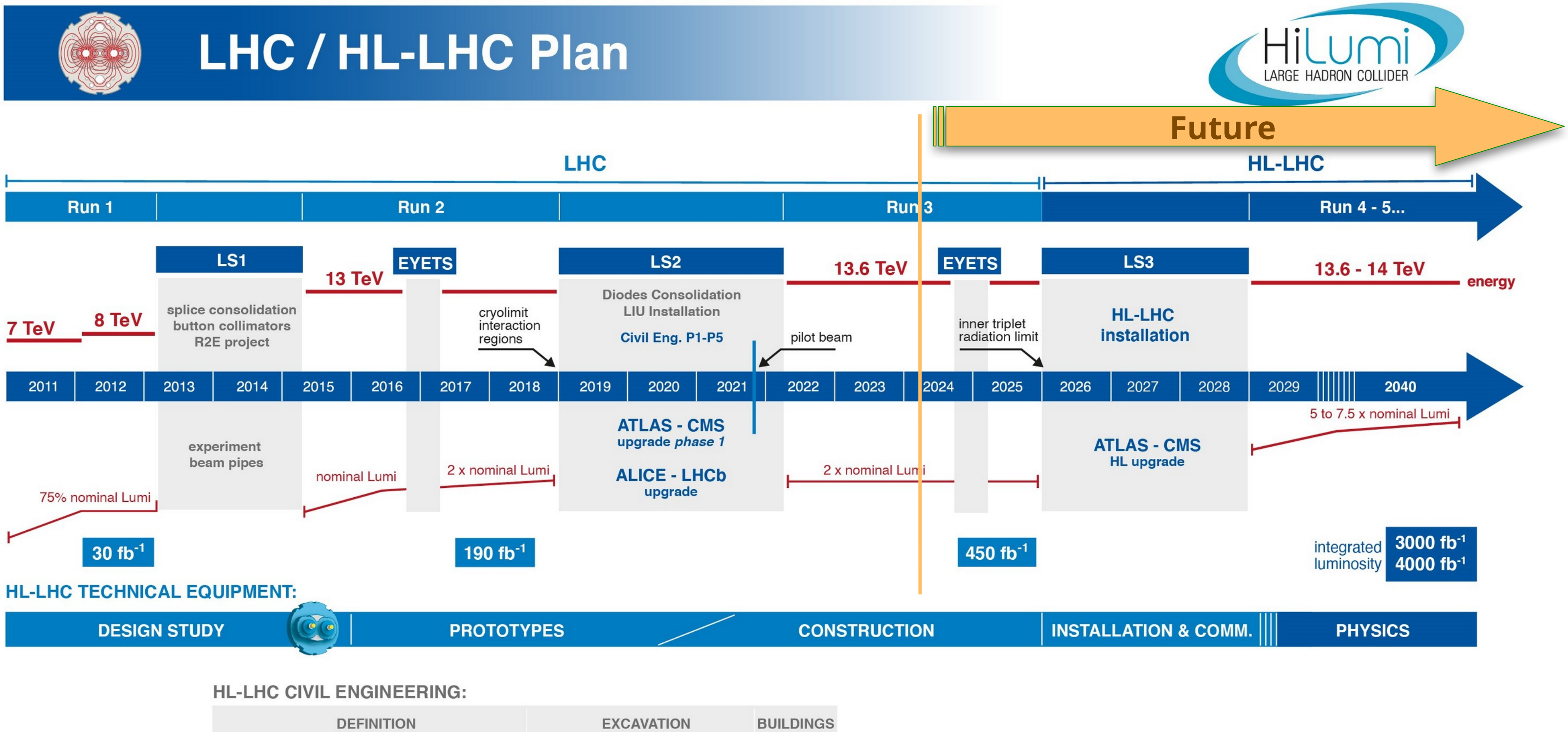


MoEDAL results

MoEDAL

- 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** [arXiv:2112.05806]

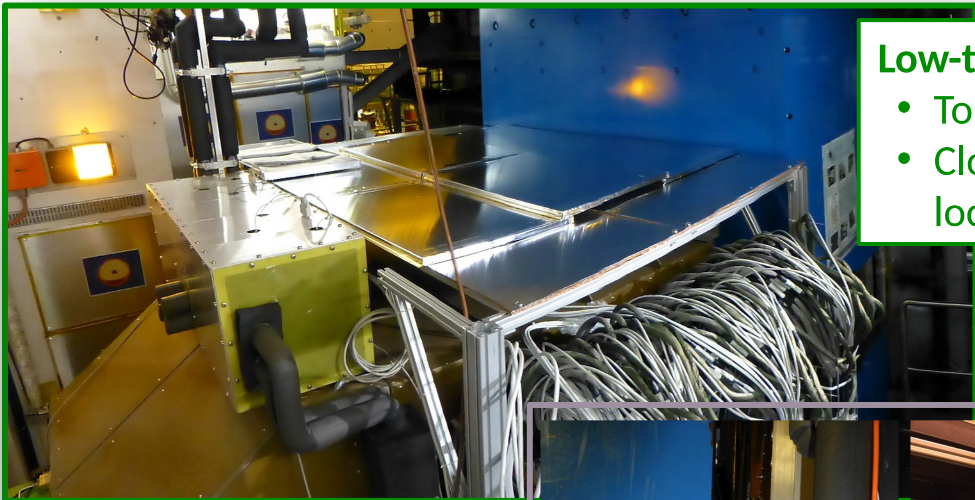
LHC & High Luminosity LHC (HL-LHC)



Run-2 NTD deployment

MoEDAL

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



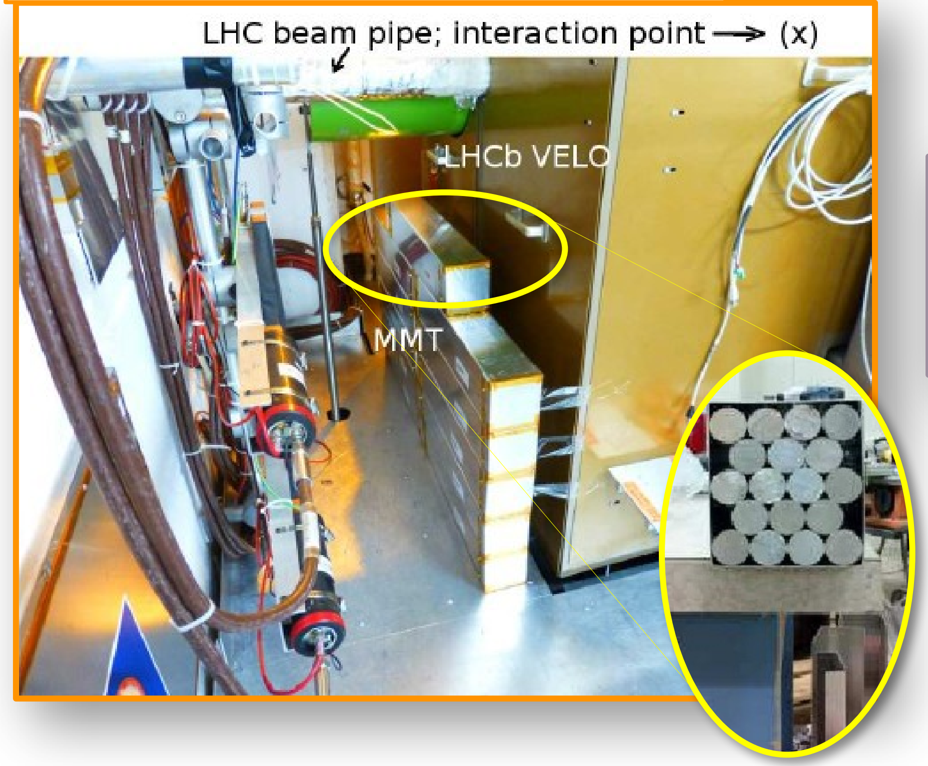
Low-threshold NTD
- Top of VELO cover
- Closest possible location to IP

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

MMTs deployment

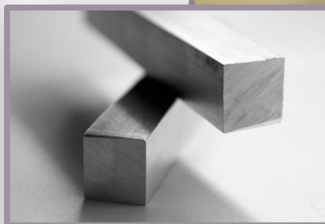
MoEDAL

Run 1 – 2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (**160 kg**)



Run 2 – 2015-2018

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

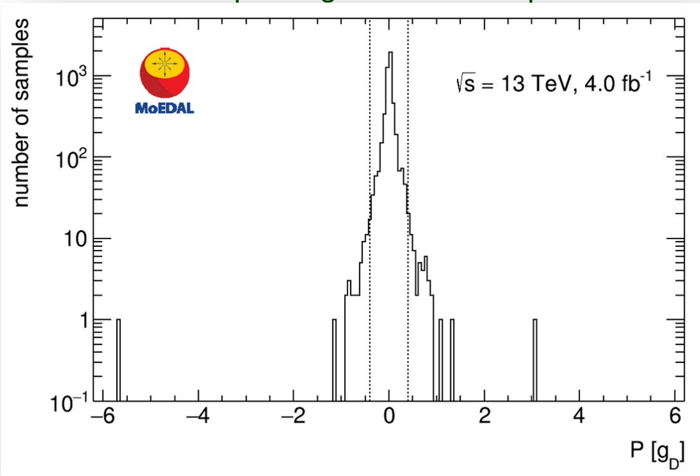


MMT scanning results

- MMTs scanned through the SQUID at the ETH Zurich Laboratory for Natural Magnetism
- MMT bars are cut into pieces and fed into the SQUID one, 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

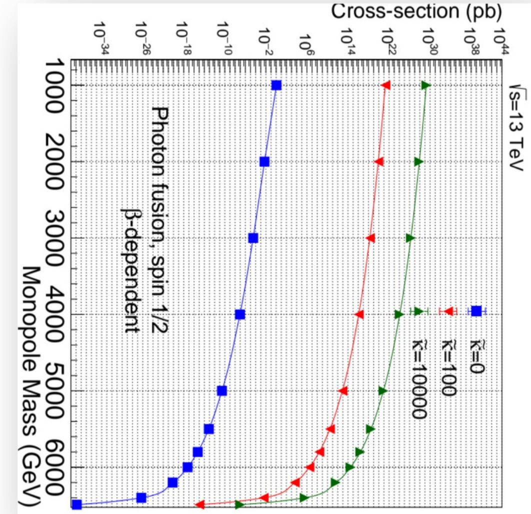
No isolated magnetic charges were found in MMT analyses

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

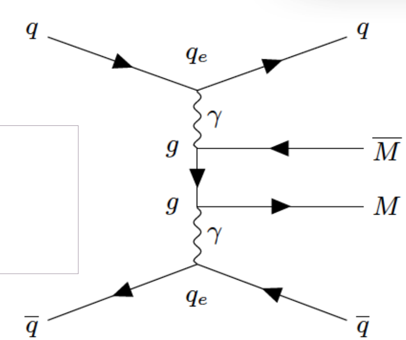


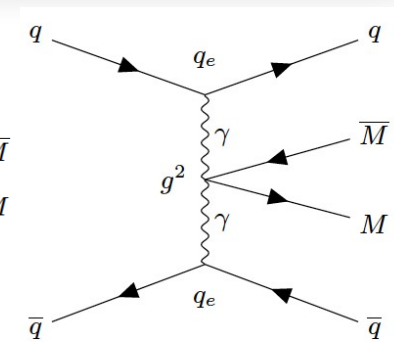
MoEDAL, PRL 123 (2019) 021802

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, $\beta \to 0$
  - parameter κ becomes very large, $\kappa \to \infty$
  - condition for perturbative coupling:
- Cross section remains finite at this limit for photon fusion while it vanishes for Drell-Yan

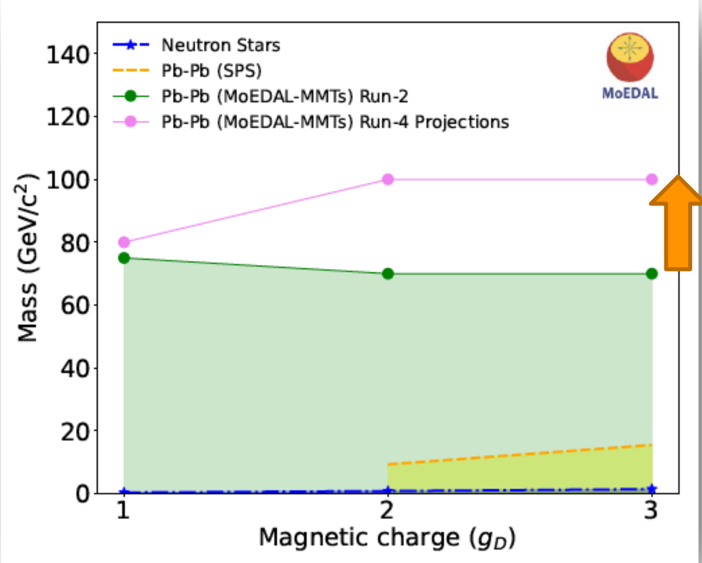




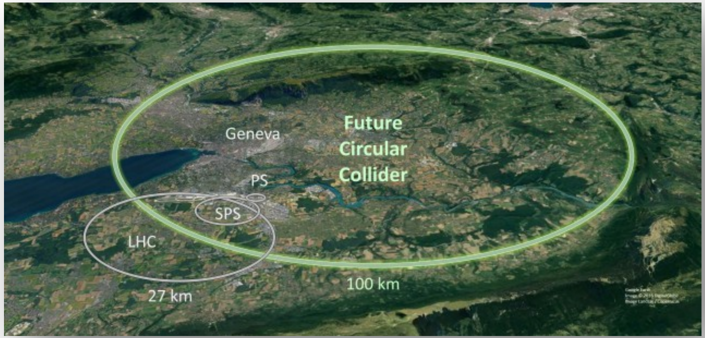
Baines, Mavromatos, Mitsou, Pinfold, Santra, Eur.Phys.J.C 78 (2018) 966

Monopoles in Schwinger mechanism – Future

- **Run-1 CMS beam pipe analysis in heavy-ion run**
- 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



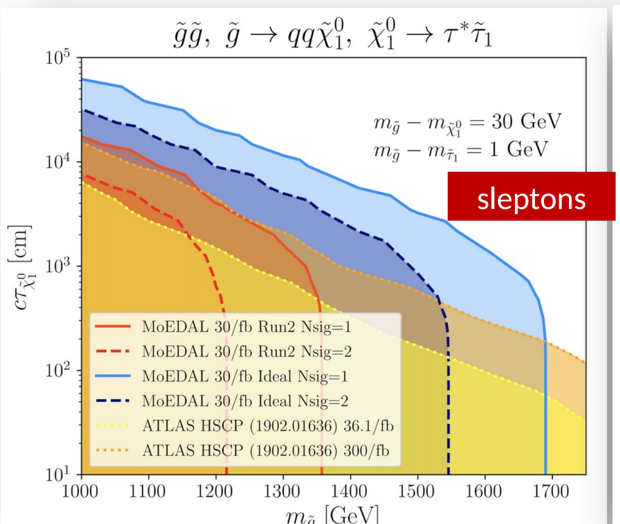
For FCC :

d' Enteria *et al, Snowmass report,* J.Phys.G 50 (2023) 050501

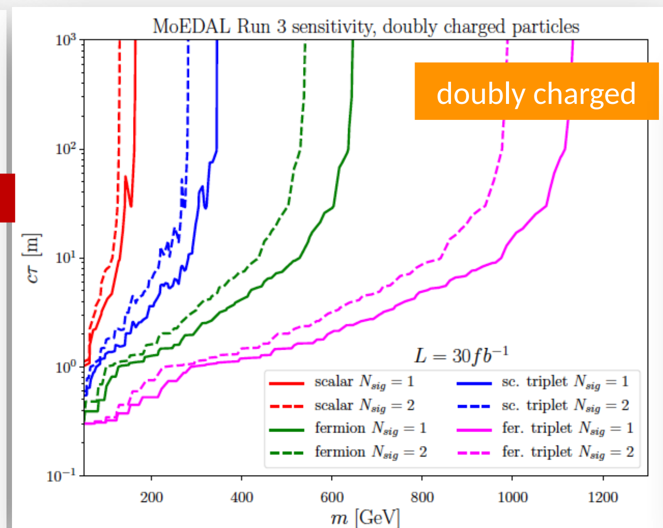
Theoretical improvements in semiclassical and fully classical approaches

Prospects for electrically charged particles

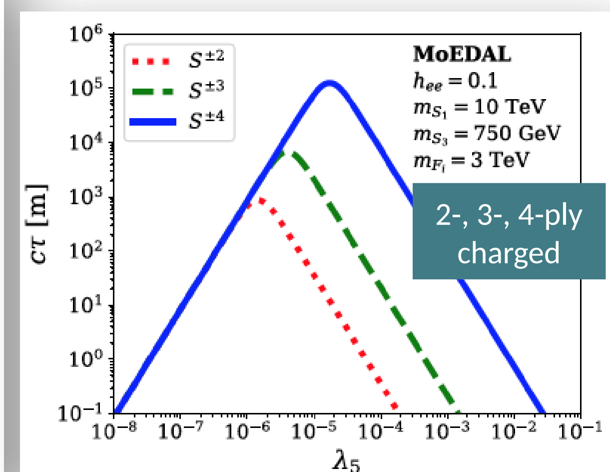
- If sufficiently slow moving, even *singly* or *multiply* ($\lesssim$ *10)* charged particles may leave a track in NTDs
- Supersymmetry offers such long-lived states: **sleptons, R-hadrons, charginos**
- Multiply charged scalars or fermions are predicted in (doubly charged) Higgs bosons and in radiative models of ν masses



Felea et al, EPJC 80 (2020) 431



Acharya et al, EPJC 80 (2020) 572



Hirsch et al, EPJC 81 (2021) 697