Hunting magnetic monopoles and more at the LHC:

Q-balls, millicharged particles, axions, …

Vasiliki A. Mitsou

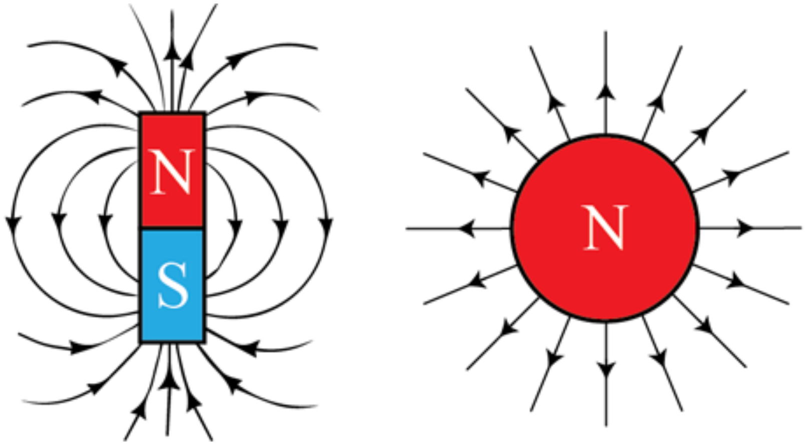
for the ATLAS and MoEDAL Collaborations

19–21 November 2021
Shanghai, China

Shanghai Particle and Cosmology Symposium 2021:

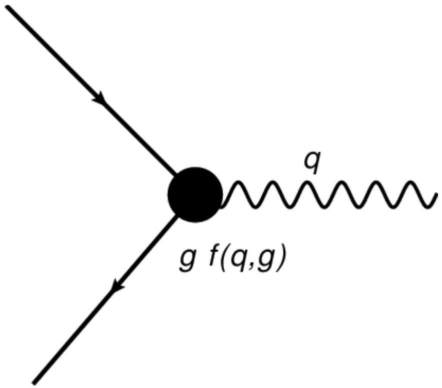
Emerging Frontiers of Axion, Dark Photon, Fractional Charged Particle and MonoPole

Magnetic monopoles



Tom Whyntie

Monopole properties in a nutshell



- 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)
  - 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 – according to the Lorentz equation

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

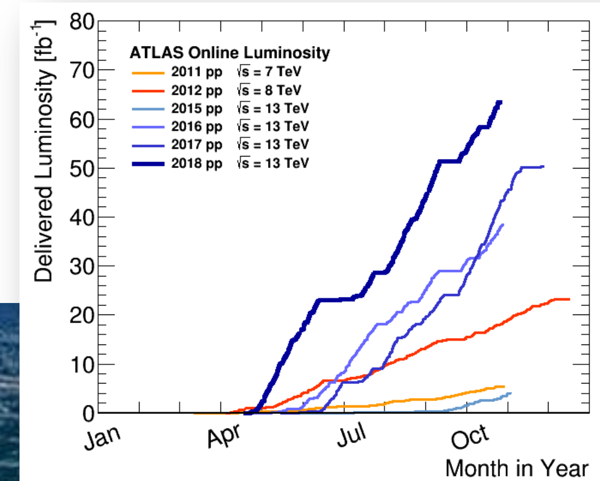
For a review on monopole theory and searches, see: Mavromatos & VAM, Int.J.Mod.Phys.A 35 (2020) 2030012

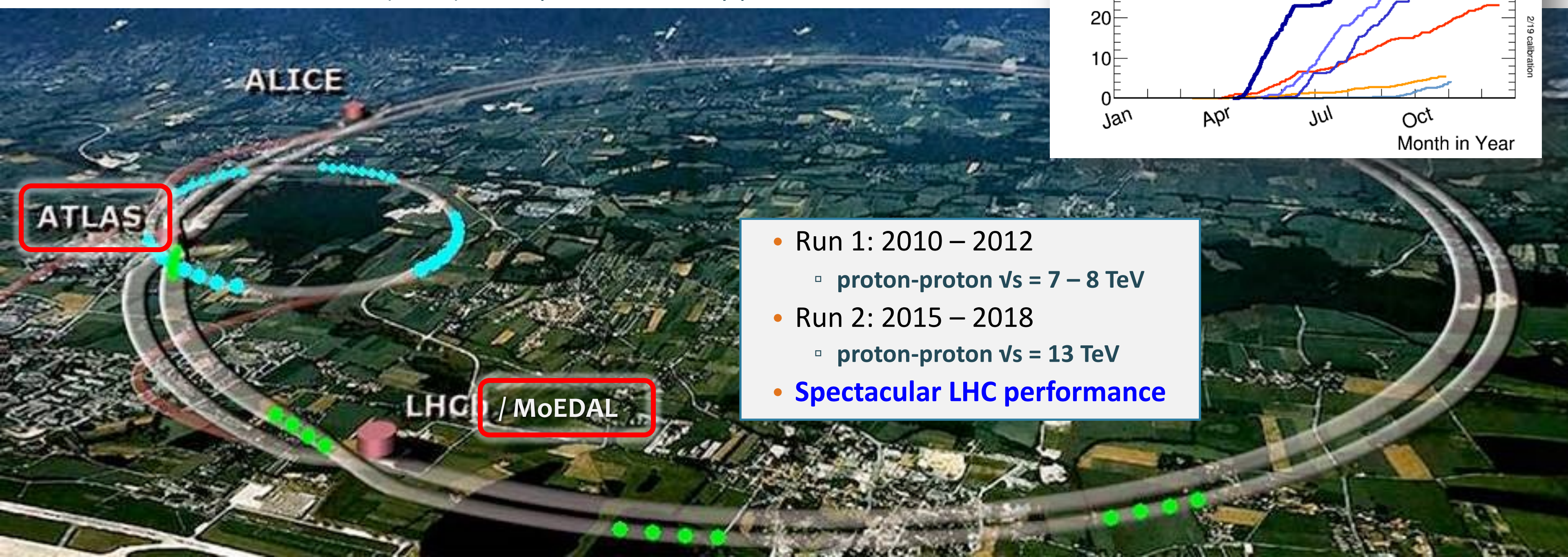
- Dirac monopole is a point-like particle; GUT monopoles are extended objects
- Monopole spin is not determined by theory → free parameter
- Monopole mass not theoretically fixed → free parameter
- Monopole interaction with matter: Cherenkov radiation, multiple scattering and **high ionisation**

For a complete introduction to monopolea, see previous talk by **Arttu Rajantie**

Large Hadron Collider at CERN

- ATLAS and MoEDAL have performed searches for magnetic monopoles
- MoEDAL receives ~50 times less luminosity than ATLAS
- Complementarity
    - ATLAS general-purpose; based on electronic readout
    - MoEDAL dedicated to (meta)stable particles; mostly passive detectors





- Run 1: 2010 – 2012
    - **proton-proton √s = 7 – 8 TeV**
- Run 2: 2015 – 2018
    - **proton-proton √s = 13 TeV**
- **Spectacular LHC performance**

ATLAS search @ 13 TeV

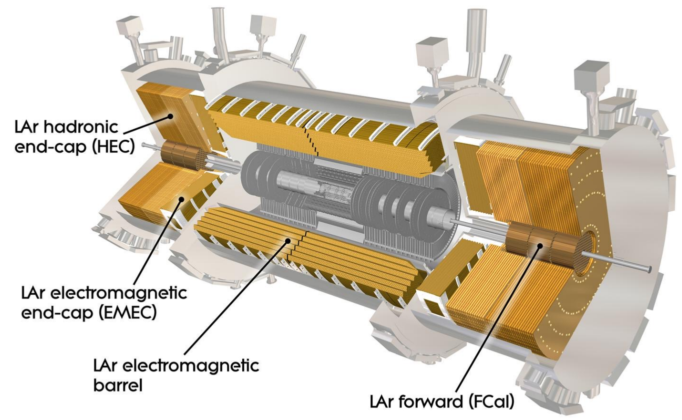
Phys.Rev.Lett. 124 (2020) 3, 031802 [arXiv:1905.10130]

Detectors for highly ionising particles (HIPs)

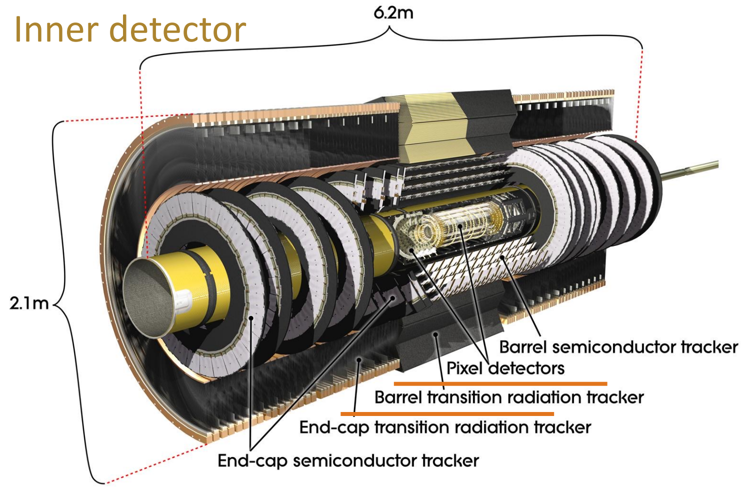
ATLAS monopole searches are based on high ionisation deposits measured in:

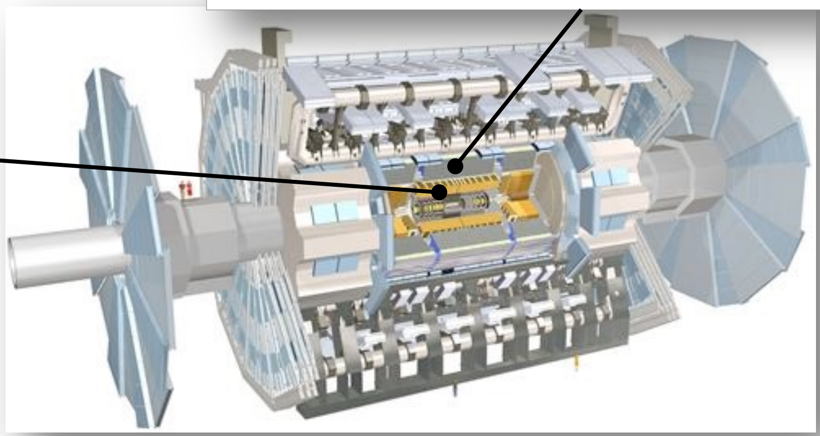
- electronic calorimeter (EM calorimeter)
  - lead–liquid Argon with accordion geometry
- transition radiation tracker (TRT)
  - Xe-filled or Ar-filled straw drift tubes
  - outermost part of the inner detector

Electromagnetic calorimeter



Inner detector



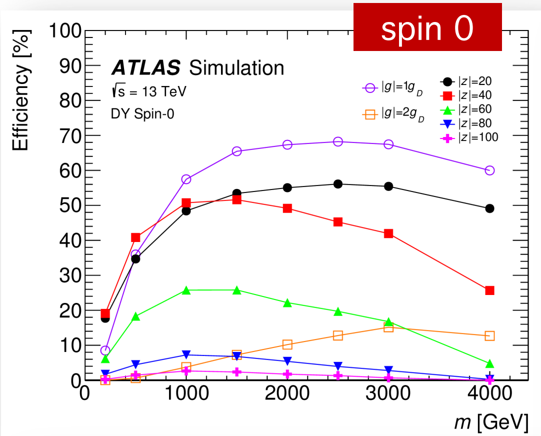


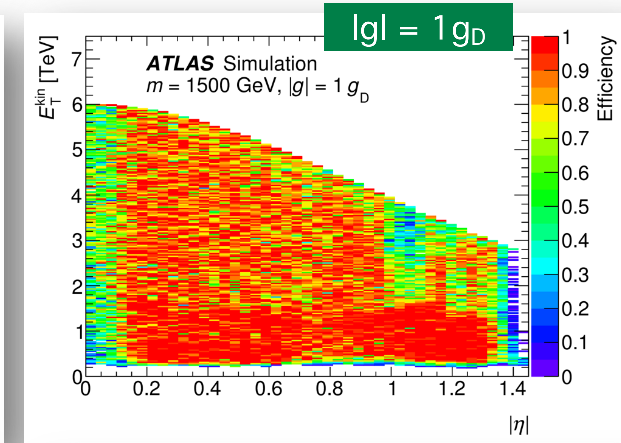
High ionisation signals

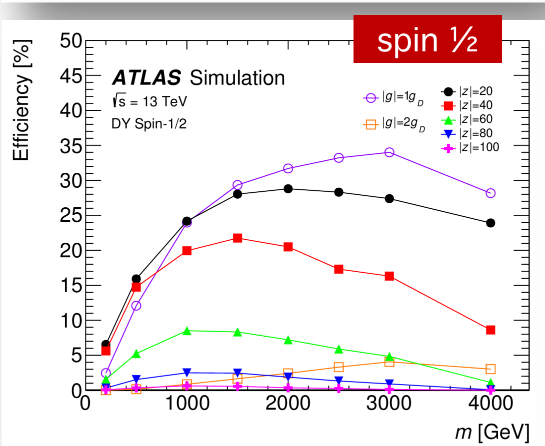
- Two different signals in
  - TRT: large high-threshold (HT) hit fraction, f_{HT}, due to HIP & associated δ-electrons
  - EM calorimeter: HIPs slow down (and usually stop) there, leaving a pencil-shape energy deposit, unlike extensive showers from (much lighter) electron
    - *w*: energy-dispersion variable; expresses the fraction of EM cluster energy contained in the most energetic cells in the EM presampler, EM1 and EM2 layers, when energy is well above cluster-level noise
- **Trigger** based on number and fraction of TRT HT hits in a narrow region around the EM calorimeter region of interest
  - hadronic calorimeter veto applied
- **Offline selection** enhanced using combination of $\boldsymbol{f_{HT}}$ and energy dispersion of the EM cluster $\boldsymbol{w}$
- Background from
  - overlapping charged particles and noise in TRT straws
  - high-energy electrons and noise in EM calorimeter cells
- Data-driven background estimation based on ABCD method in the (w, f_{HT}) plane

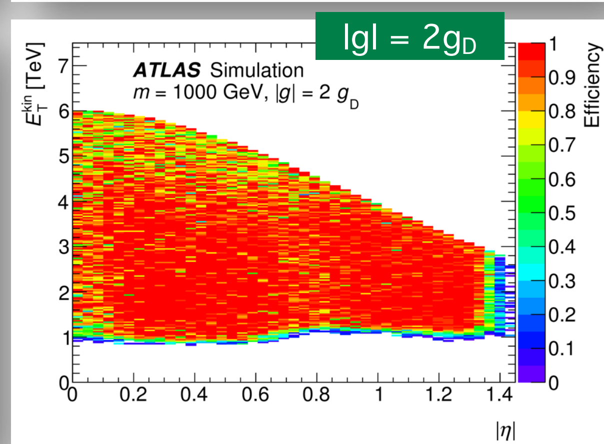
Phys.Rev.Lett. 124 (2020) 031802

Signal efficiency









Signal loss due to

- high HIP charge: stop before EM calorimeter
- low HIP charge: too little energy deposited in EM calorimeter, or penetrate reaching hadronic calorimeter, invoking veto

Selection efficiency = fraction of MC events surviving the trigger and offline selection criteria

Phys.Rev.Lett. 124 (2020) 031802

Results

- Results based on 2015+2016 data (34.4 fb^{-1})
- No events observed in signal region A

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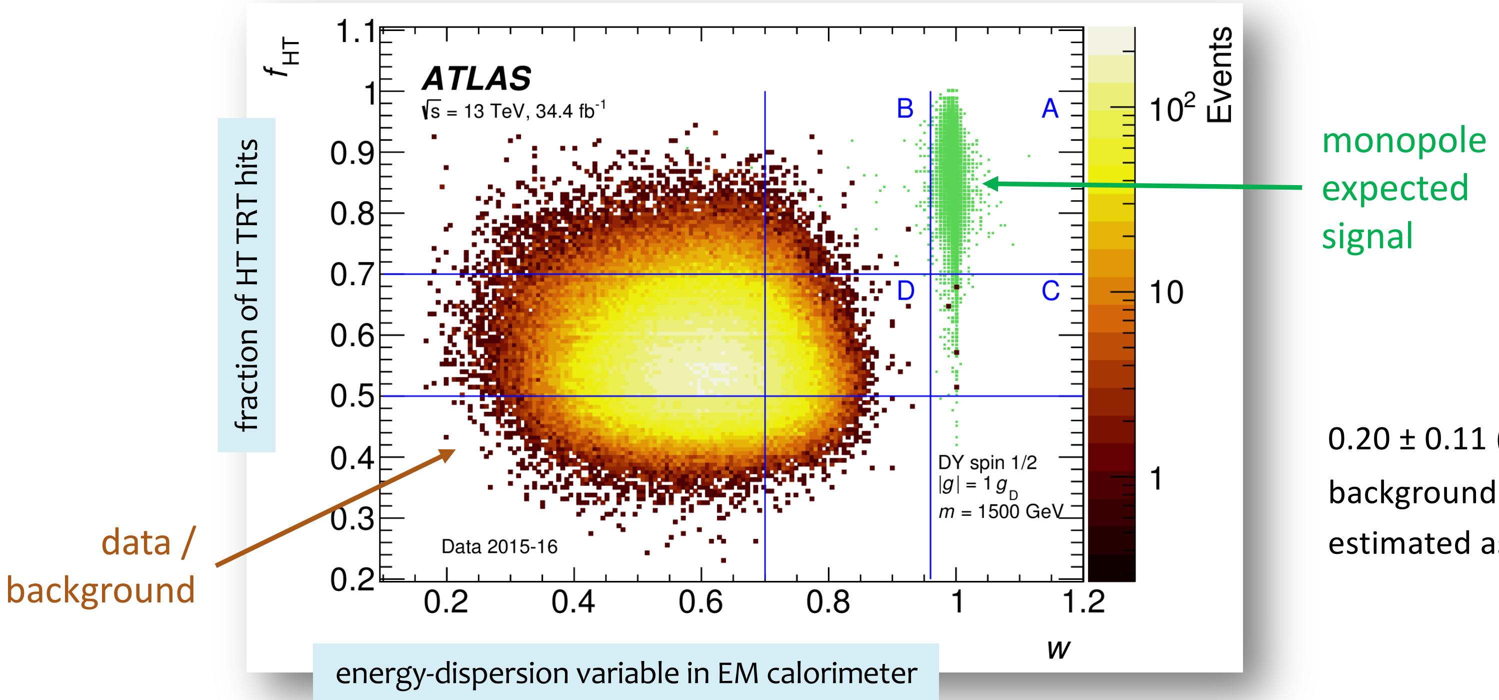
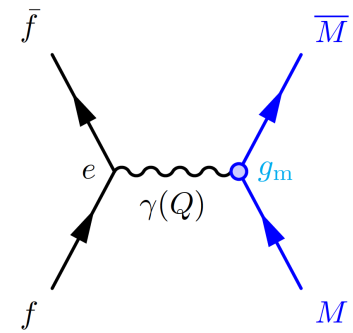


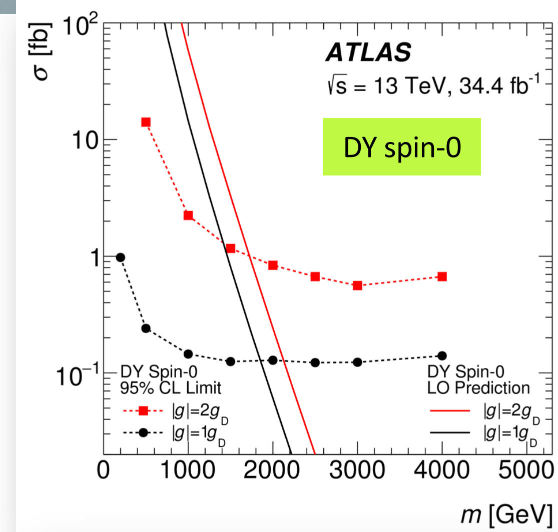
0.20 ± 0.11 (stat) ± 0.40 (sys) background events expected, estimated as $N_A^{exp} = N_B N_C / N_D$

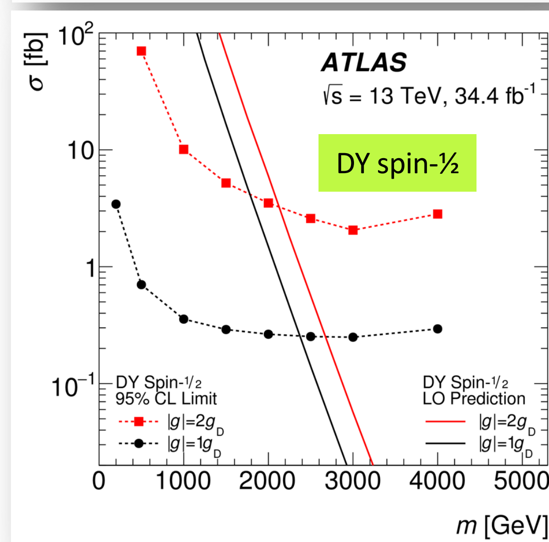
Interpretation

- Magnetic charges probed: $1 < |g| < 2.0\ g_D$
- Upper limits on production cross section set, assuming Drell-Yan (DY) spin-0 and spin-½ kinematics, as a function of monopole mass
- Lower limits on mass set for Dirac monopoles for DY production & β-independent γ-*M* coupling

Drell–Yan lower mass limits [GeV]		
	$g = 1g_D$	$g = 2g_D$
spin-0	1850	1725
spin ½	2370	2125







Strongest limits on monopoles of charge 1-2 g_D !

Mass limits based on Feynman-*like* diagrams, where perturbative calculations are impossible due to large γ-monopole coupling. They *only* serve to facilitate comparisons.

Phys.Rev.Lett. 124 (2020) 031802

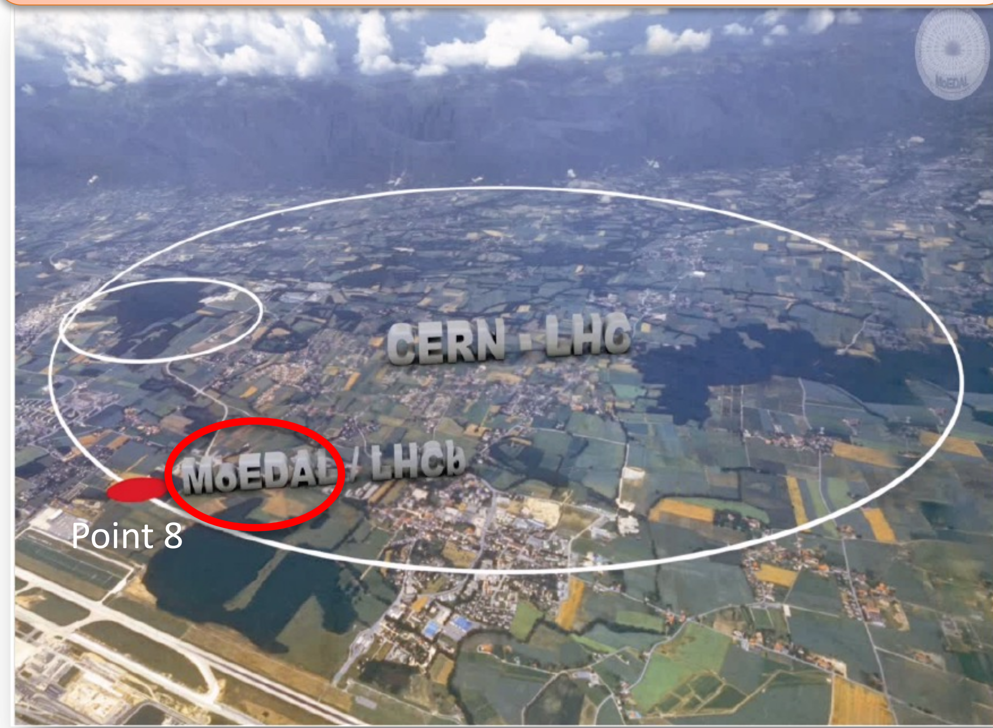
MoEDAL

MoEDAL results

- Monopole summary:
  - JHEP 1608 (2016) 067 [arXiv:1604.06645]
  - Phys.Rev.Lett. 118 (2017) 061801 [arXiv:1611.06817]
  - Phys.Lett.B 782 (2018) 510–516 [arXiv:1712.09849]
- Dyons, Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]
- Schwinger mechanism, arXiv:2106.11933, *submitted to Nature*

MoEDAL – Monopole & Exotics Detector At LHC

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

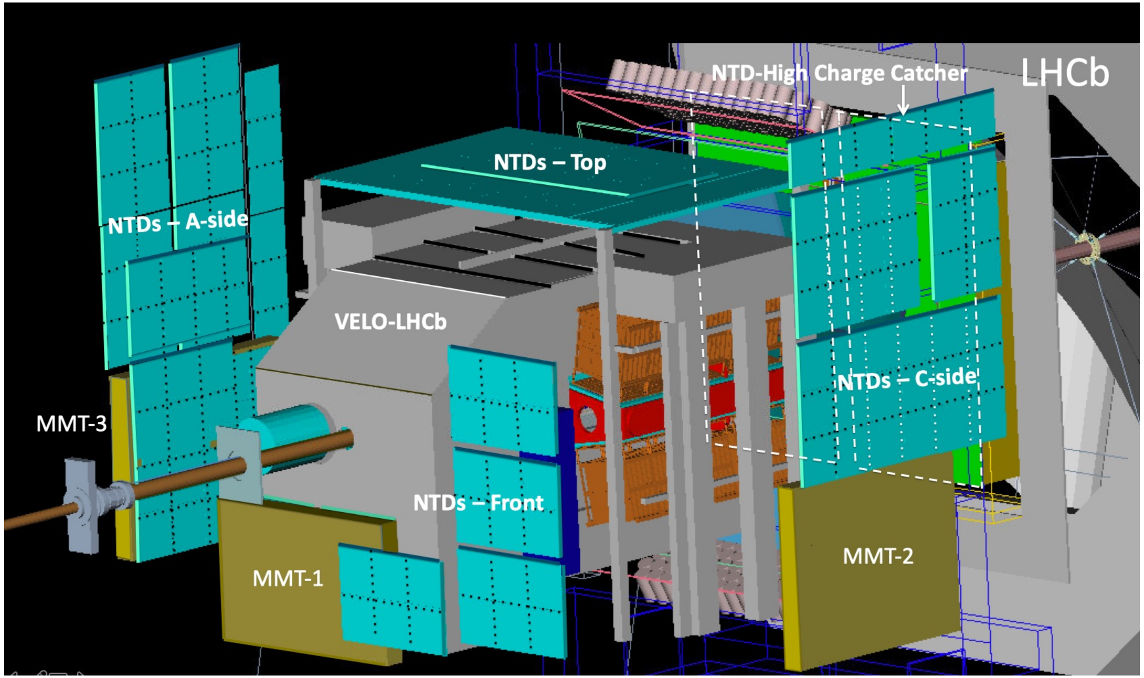


Optimised for anomalously ionising (meta)stable particles

- **Highly ionising particles** – magnetic & electric charges
  - magnetic monopoles
  - SUSY sleptons & R-hadrons
  - doubly charged Higgs
  - ν mass models
  - KK extra dimensions
  - D matter
  - black-hole remnants
- **Very low ionisation → MAPP**
  - *fractional* electric charges
  - displaced vertices from *neutral* particles

MoEDAL

Baseline MoEDAL detector



MoEDAL

DETECTOR SYSTEMS

① Low-threshold NTD (**LT-NTD**) array
- z/β > ~5-10

② Very High Charge Catcher NTD (**HCC-NTD**) array
- z/β > ~50

③ **TimePix** radiation background monitor

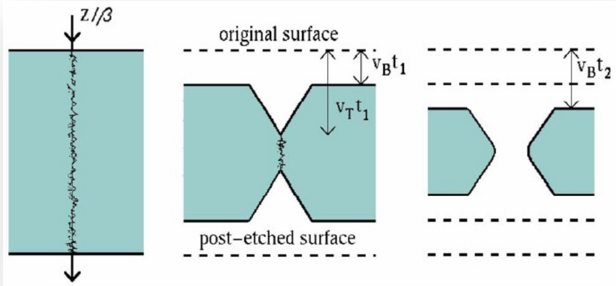
④ Monopole Trapping detector (**MMT**) – aluminum bars

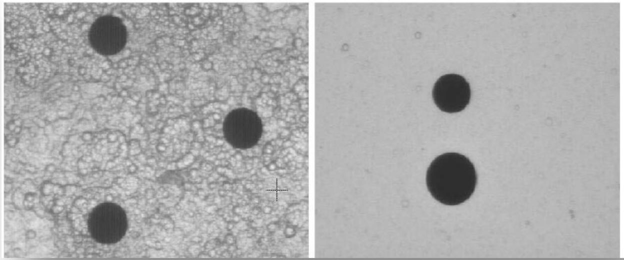
- Mostly **passive detectors**; no trigger; no readout
- Permanent physical record of new physics
- No SM physics backgrounds

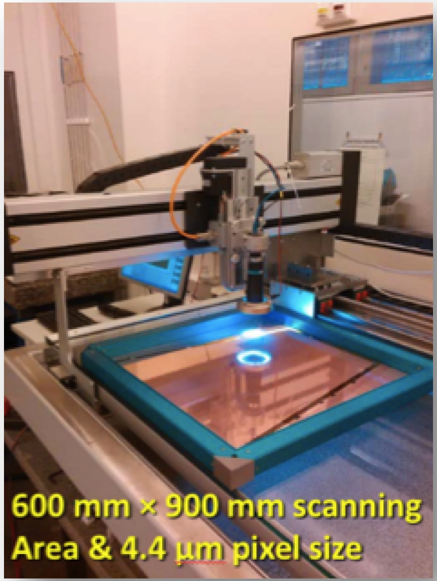
MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050

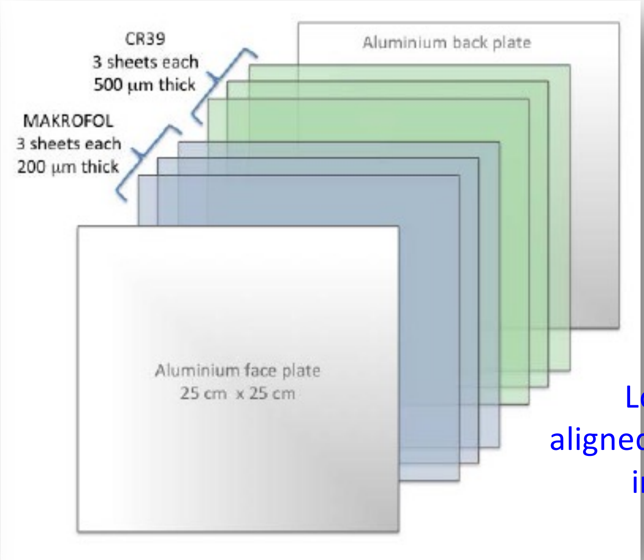
Nuclear Track Detectors (NTDs)

- 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

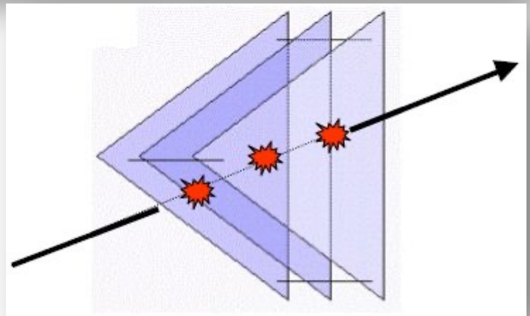






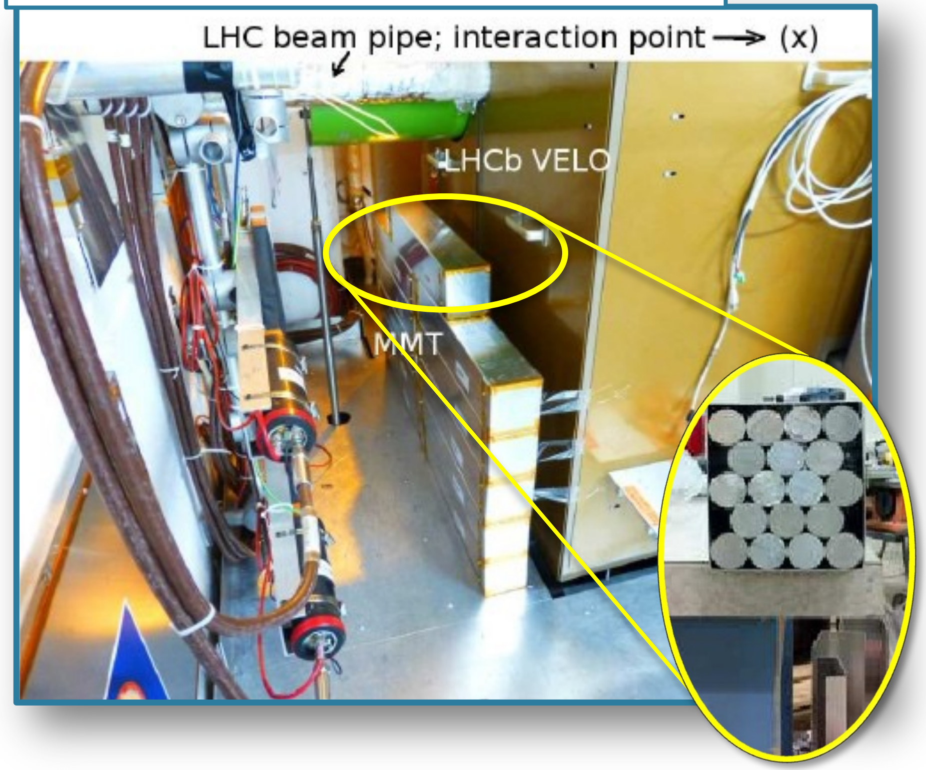


Looking for aligned etch pits in multiple sheets



MMTs deployment

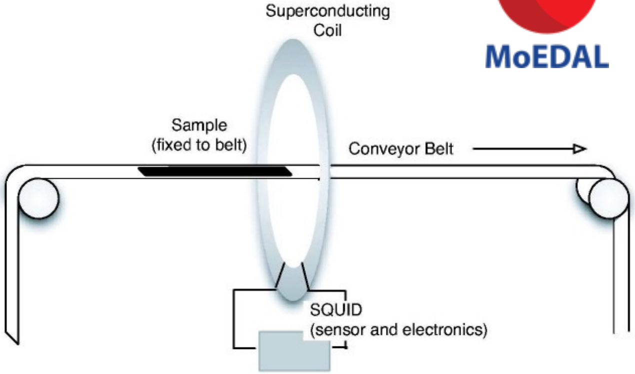
2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (**160 kg**)



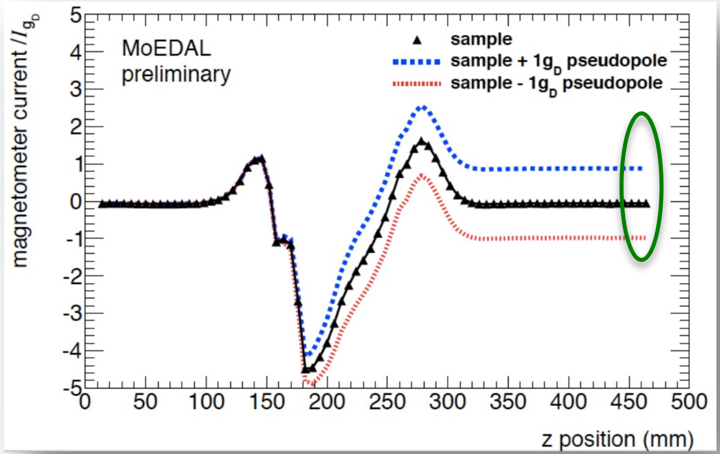
2015-2018
- Installed in forward region under beam pipe & in **sides A & C**
- Approximately **800 kg** of aluminium
- Total 2400 aluminum bars

Induction technique results

- Monopoles can bind to nuclei and get trapped
- MMTs scanned through super-conducting quantum interference device (SQUID) at ETH Zurich
- **Persistent current:** difference between current after and before

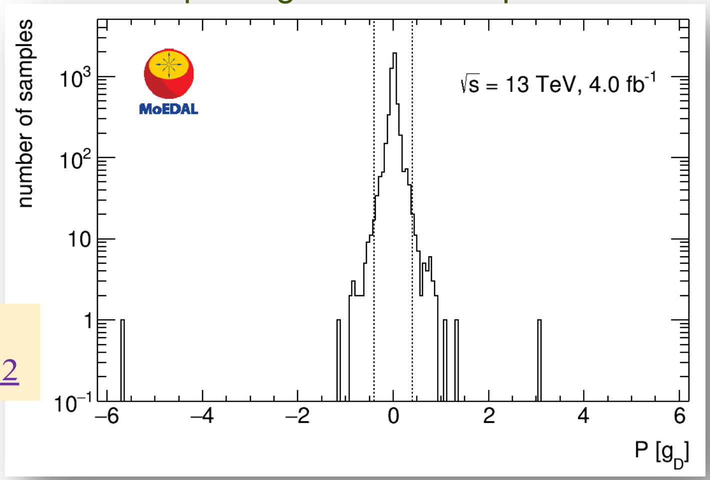


Calibration: typical sample & pseudo-monopole curves



MoEDAL, PRL 123 (2019) 021802

Persistent current after first two passages for all samples

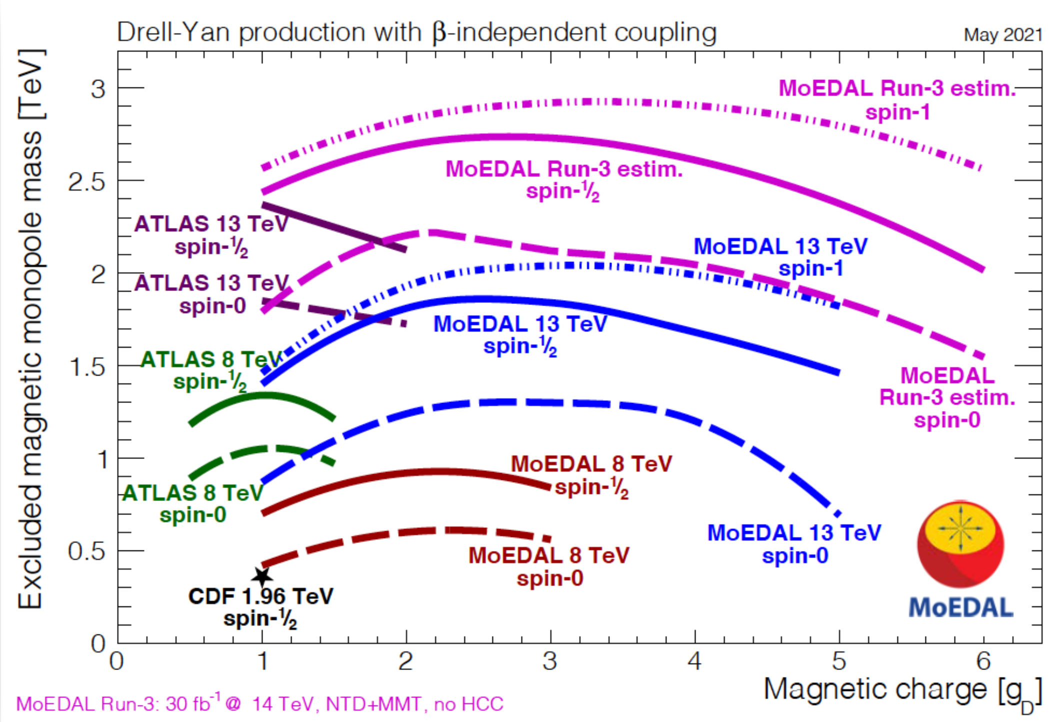


Magnetic monopole limits

Novelties in monopole models considered w.r.t. other experiments

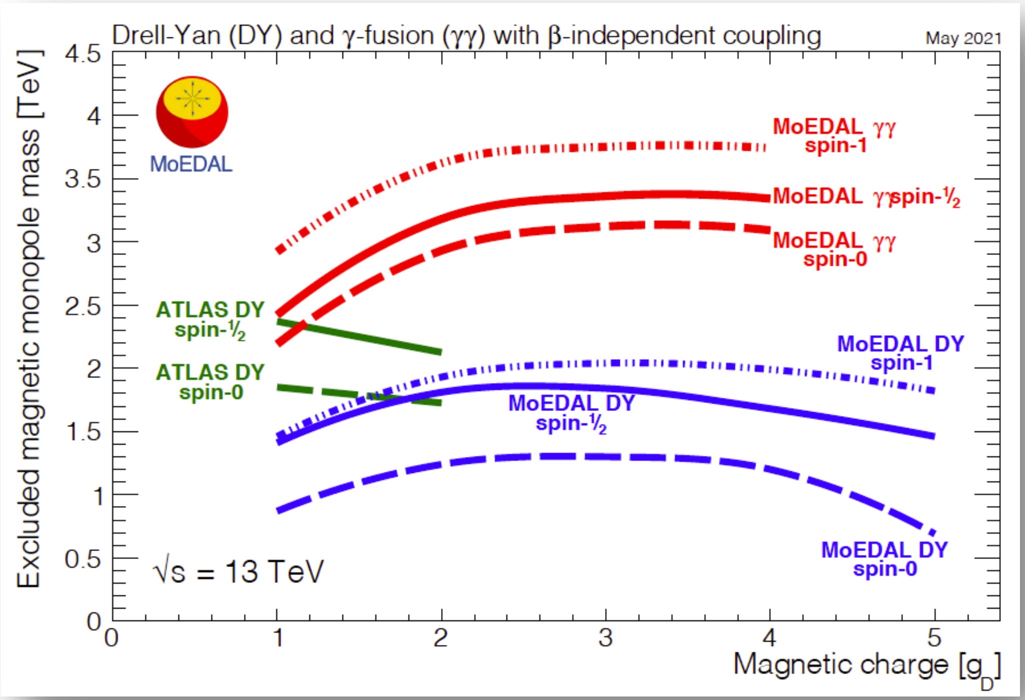
- β-dependent coupling
- spin-1 monopoles
- γγ fusion

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

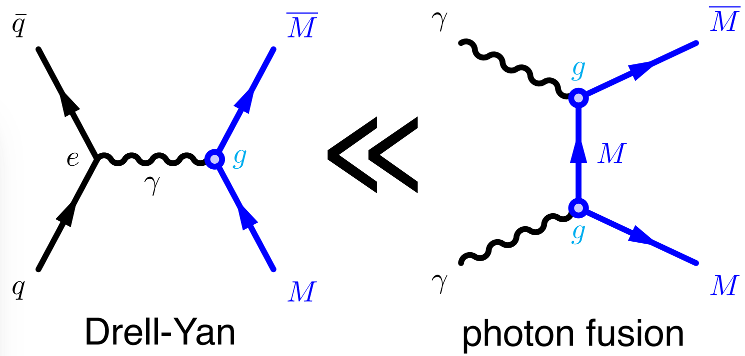


MoEDAL, JHEP 1608 (2016) 067, PRL 118 (2017) 061801, PRL 123 (2019) 021802

Drell-Yan & γγ-fusion



MoEDAL, Phys.Rev.Lett. 123 (2019) 021802 [arXiv:1903.08491]



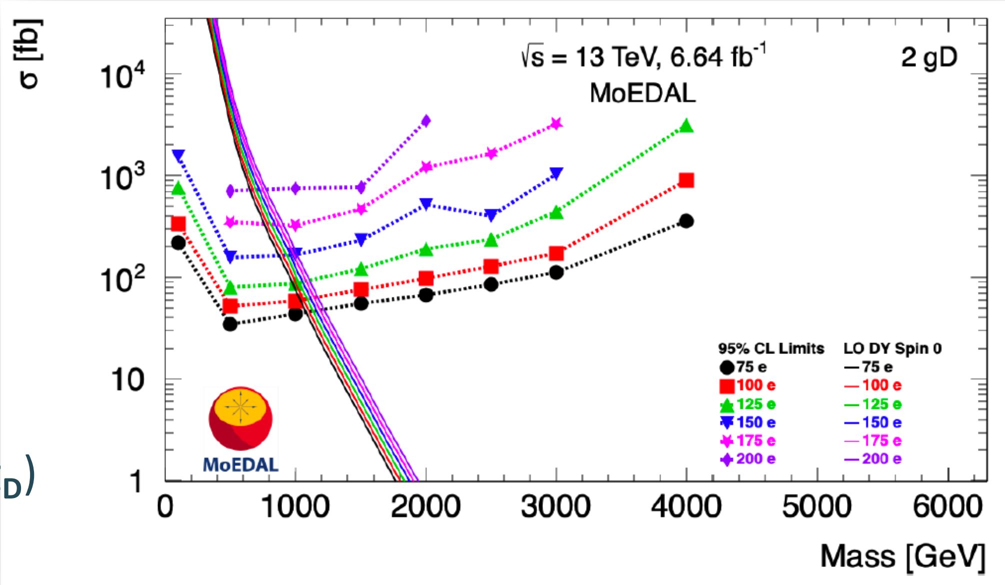
Photon-fusion monopole production process has much higher cross section than Drell-Yan-like at the LHC c.m.s. energies

Extended reach by combining Drell-Yan and γ-fusion production processes

Dyon search

First explicit accelerator search for direct dyon production

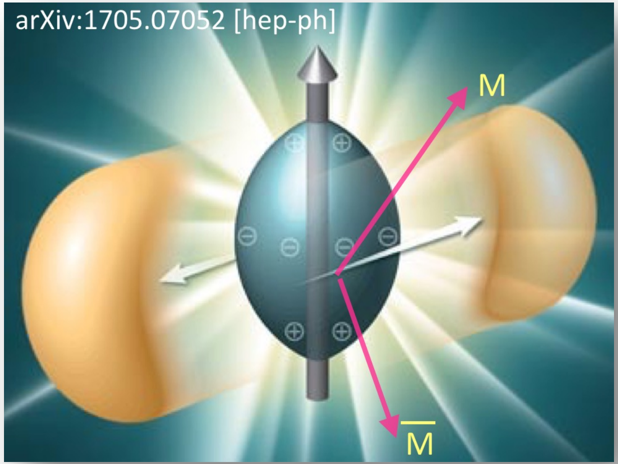
- Dyons possess both electric and magnetic charge
- MMT scanning searching for captured dyons
  - 6.46 fb^{-1} of 13 TeV *pp* collisions during 2015-2018
- Analysis considered
  - dyons of spin 0, ½, 1
  - Drell-Yan production
- Excluded cross sections as low as **30 fb**
- Mass limits **750-1910 GeV**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

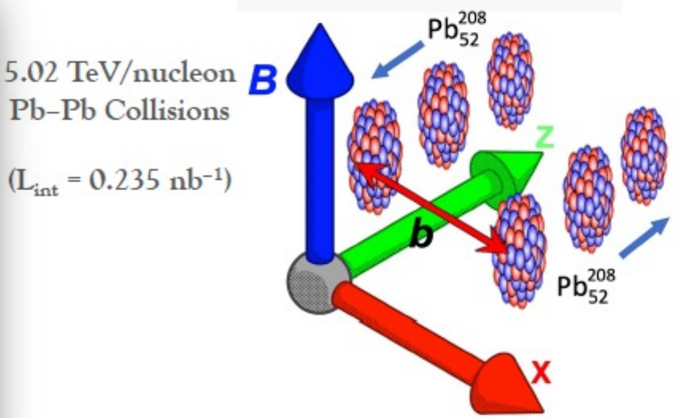


MoEDAL, Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]

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

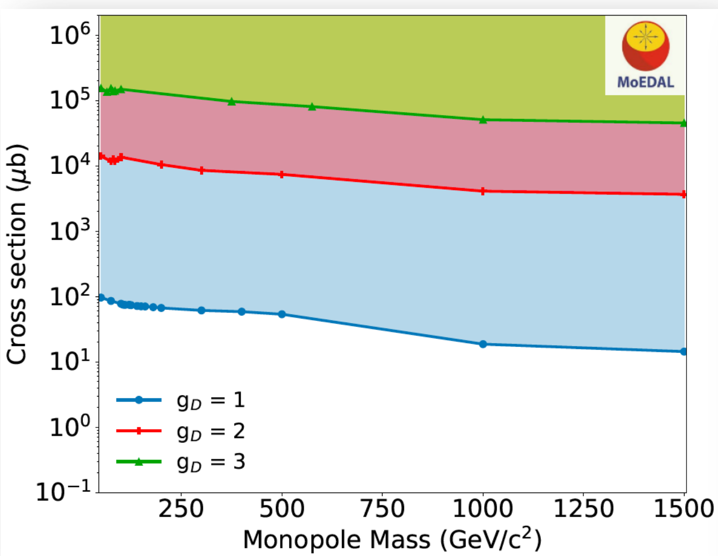
- cross-section calculation using semiclassical techniques ⇒ does not suffer from non-perturbative nature of coupling
- no exponential suppression $e^{-4/\alpha}$ for finite-sized monopoles

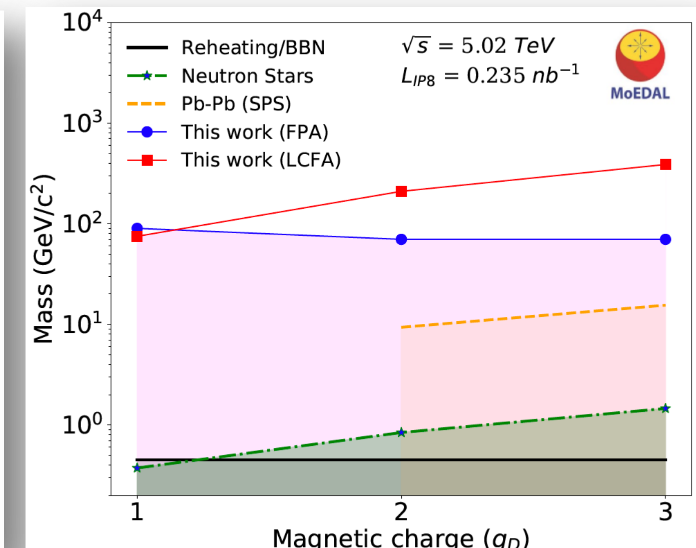
Gould, Ho, Rajantie, PRD 100, 015041 (2019), arXiv:2103.14454
Ho & Rajantie, PRD 101, 055003 (2020), PRD 103 (2021) 11, 115033

For a theoretical description, see previous talk by **Arttu Rajantie**

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

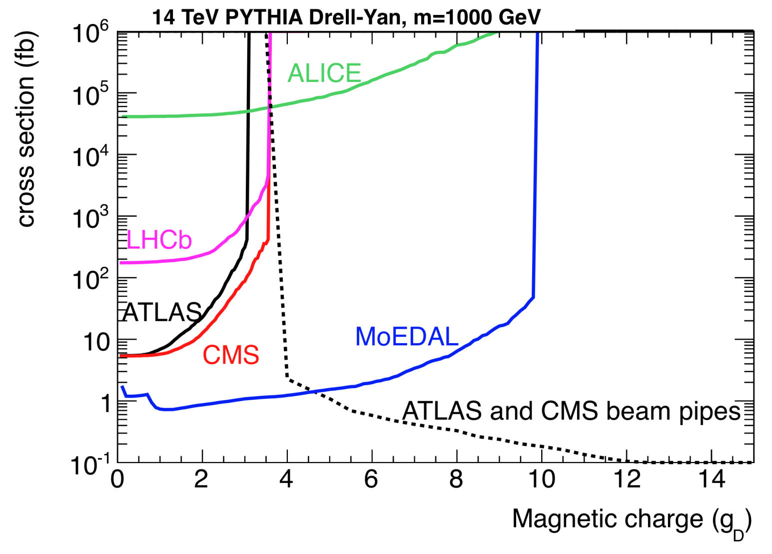
MoEDAL, arXiv:2106.11933, submitted to *Nature*

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
Interpretation in progress



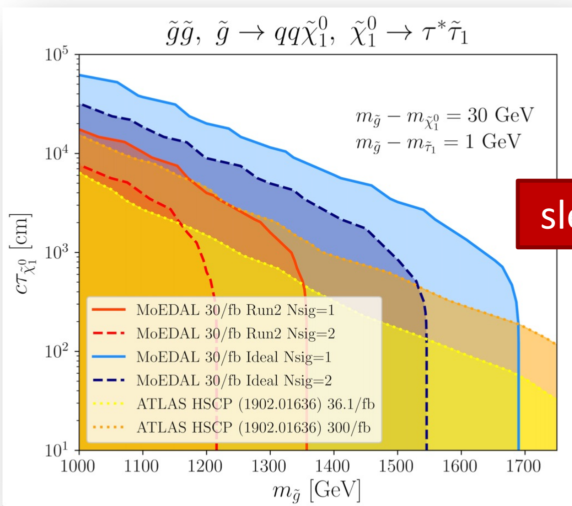
De Roeck et al, EPJC72 (2012) 1985

CERN Courier, Mar-Apr 2019

Electrically charged particles

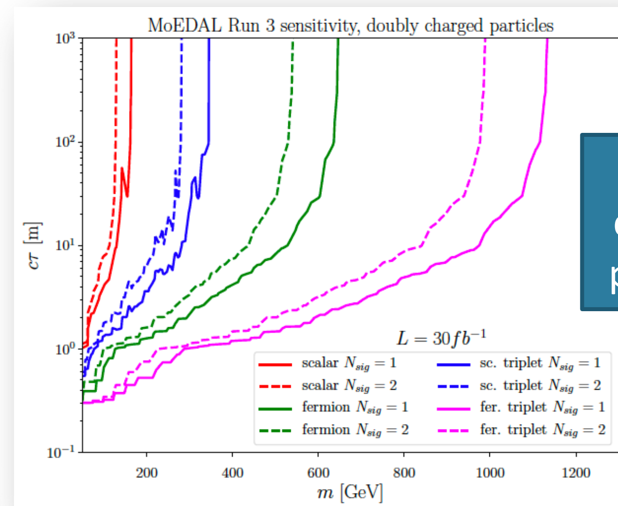
- If sufficiently slow moving, *singly* or *doubly* charged particles may leave a track in NTD
- Supersymmetry offers such long-lived states: **sleptons, R-hardons, charginos**
- Doubly charged scalars or fermions are predicted in type-II seesaw models of ν masses
- **MoEDAL can complement ATLAS/CMS reach in longer-lifetime region**

Felea et al, Eur.Phys.J.C 80 (2020) 431



sleptons

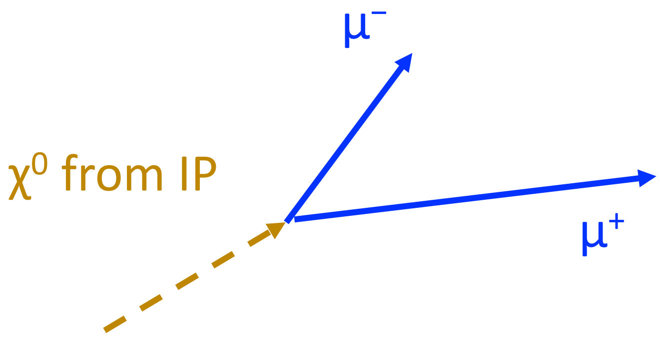
Acharya et al, Eur.Phys.J.C 80 (2020) 572



doubly charged particles

Results on **Highly Electrically Charged Objects (HECOs), e.g. Q-balls,** in final stages of approval in MoEDAL→ First MoEDAL analysis with NTDs !

MoEDAL MAPP

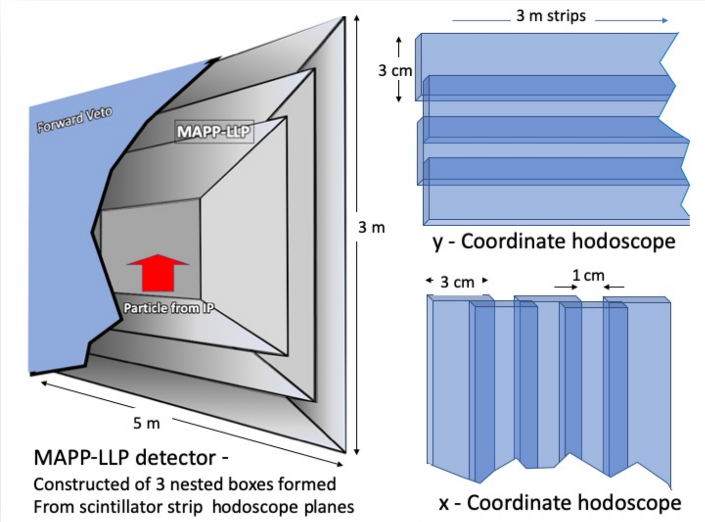


MAPP– MoEDAL Apparatus for Penetrating Particles

Consists of two subdetectors:

- core millicharged particle detector **MAPP-mQP**
  - particles with charges ≪ ***1e*** leaving a trace of low ionisation
- very long-lived weakly interacting neutral particle detector **MAPP-LLP**

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



MAPP-LLP detector -
Constructed of 3 nested boxes formed
From scintillator strip hodoscope planes

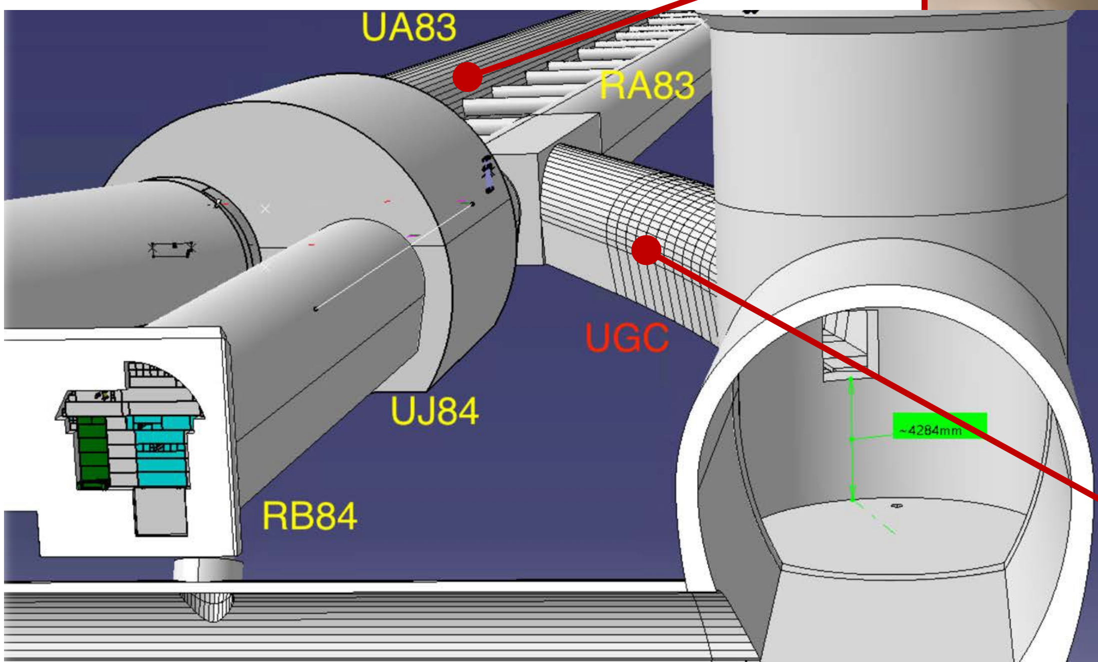
Prototype mQP installed in 2017 in UGC1 gallery

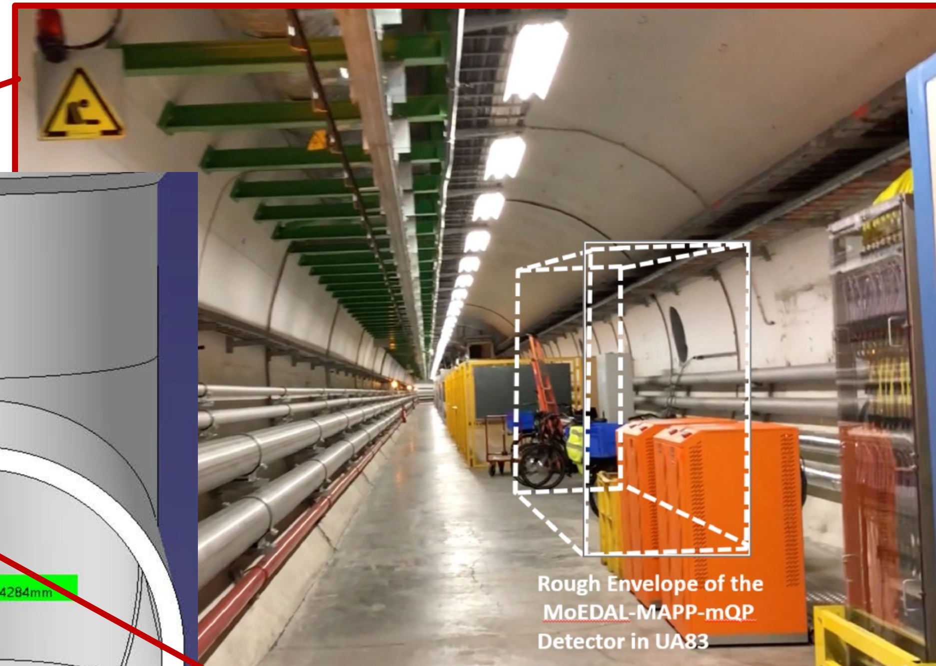
- 3×3 bars (~30×30 cm)
- ~10% of full detector

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

MAPP possible location in UA83

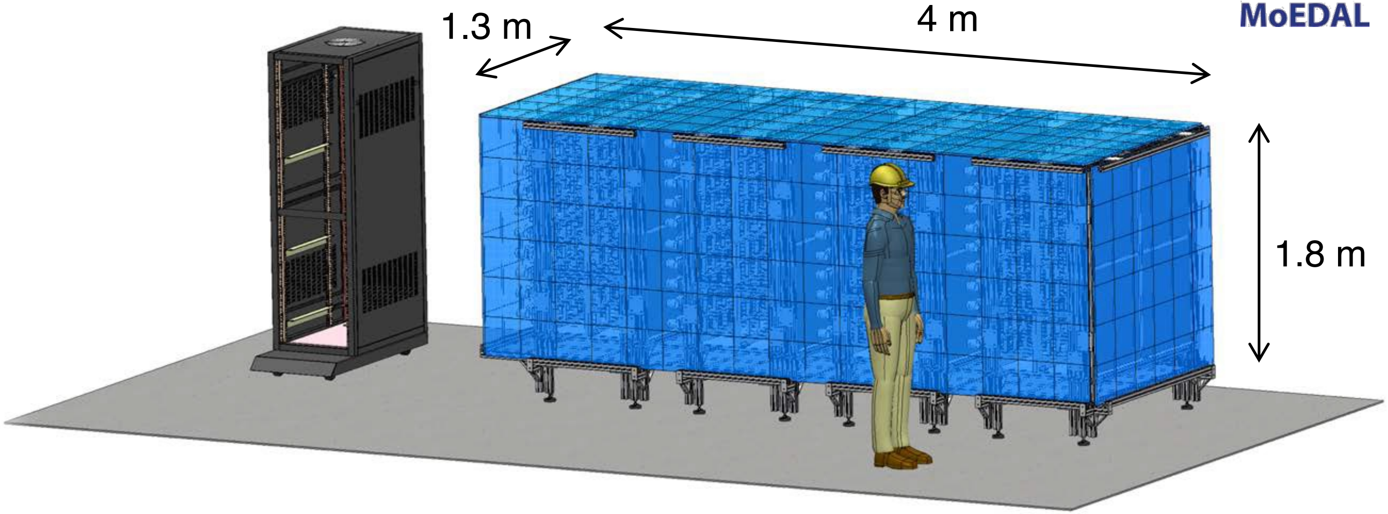
- Easily accessible gallery, already fitted out
- Access independent from LHCb





previous position
(mQP 2017 prototype)

MAPP-mQP detector

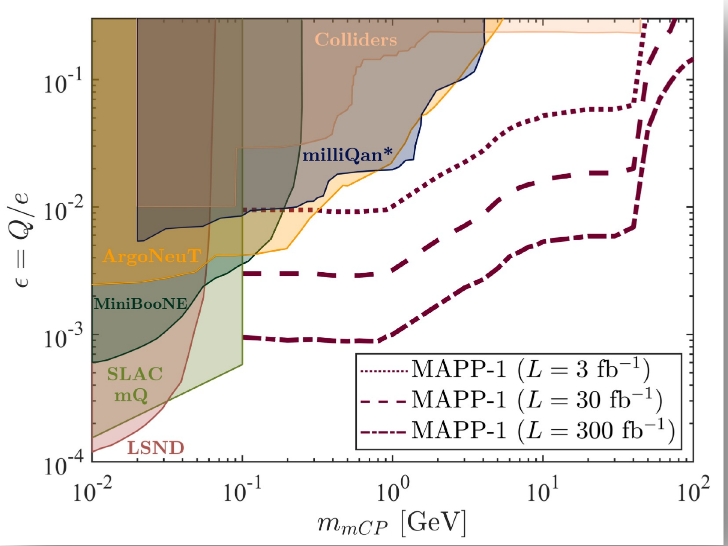


complete section

- Consists of 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
- Deployed in UA83 for Run-3 ➔ 100m from IP8 at 6.5° to the beam
- Shielded by ~35 m of rock from SM backgrounds from the IP and protected from CR backgrounds by 110 m rock overburden
- MoEDAL-mQP Technical Proposal has been submitted
- Installation planned to start in December 2021

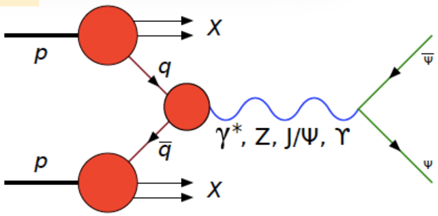
mQP & millicharged particles (mCPs)

Dark photon decays to mCPs

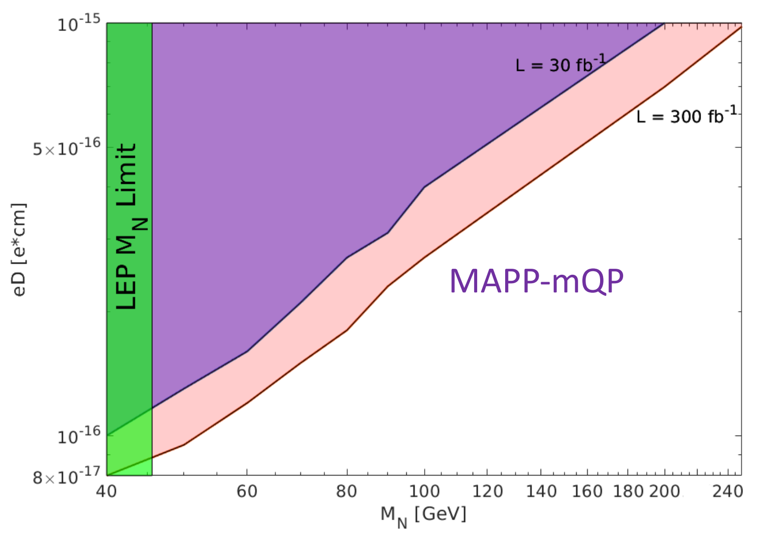


M. Staelens, PhD thesis, U. Alberta

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



Heavy neutrino with large EDM



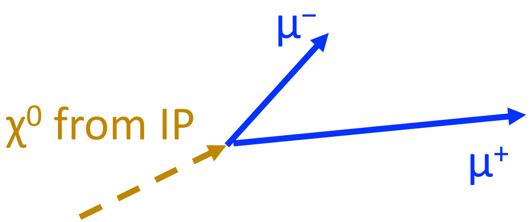
Frank et al, Phys.Lett.B 802 (2020) 135204

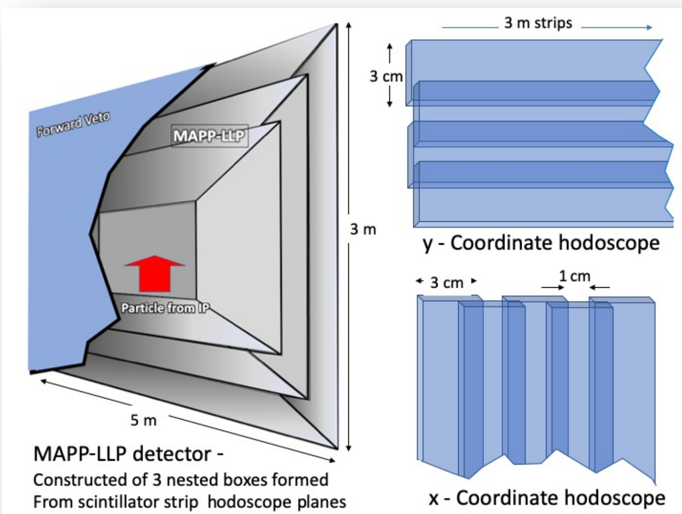
Limits that MAPP can place on heavy neutrino production with large EDM at Run-3 and HL-LHC at IP8

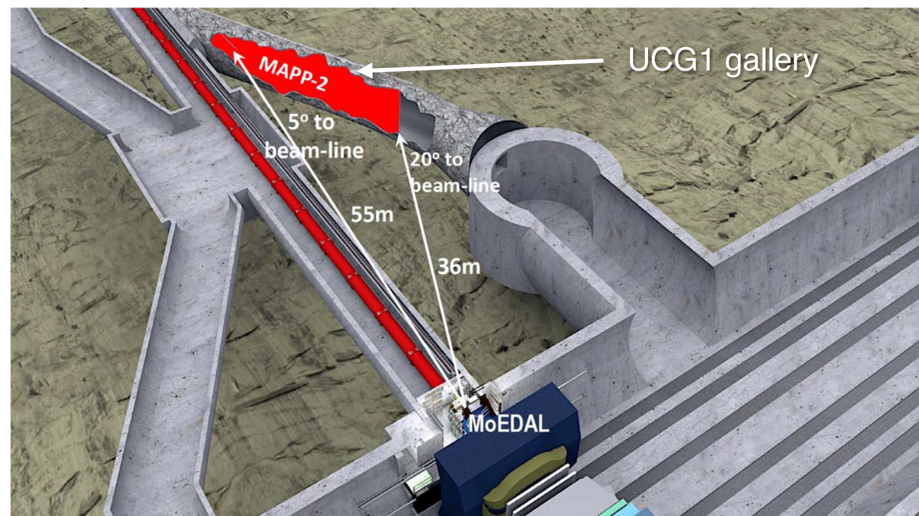
MAPP Phase 2 – LLP detector

MoEDAL

- "Box-within-a-box" structure to detect charged tracks from neutral-particle decays
- Scintillator strips in *x-y* configuration readout by SiPMs
  - resolutions ~1cm × 1cm on each hit
  - 500 ps or better timing resolution
- MAPP-2 utilises the renovated **UGC1 gallery**
- To be installed during LHC Long Shutdown 3 and run in HL-LHC

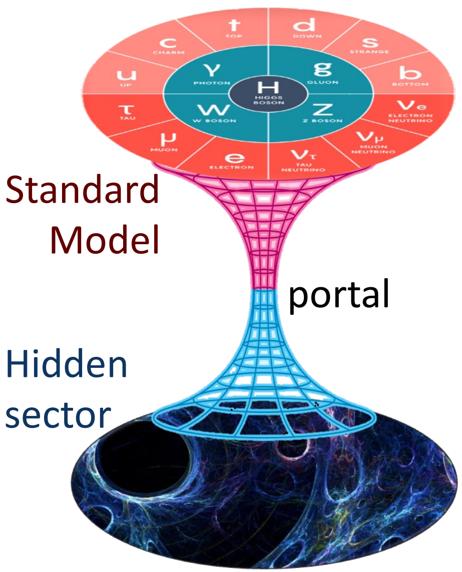






MAPP-2 sensitivity: axions, …

MoEDAL



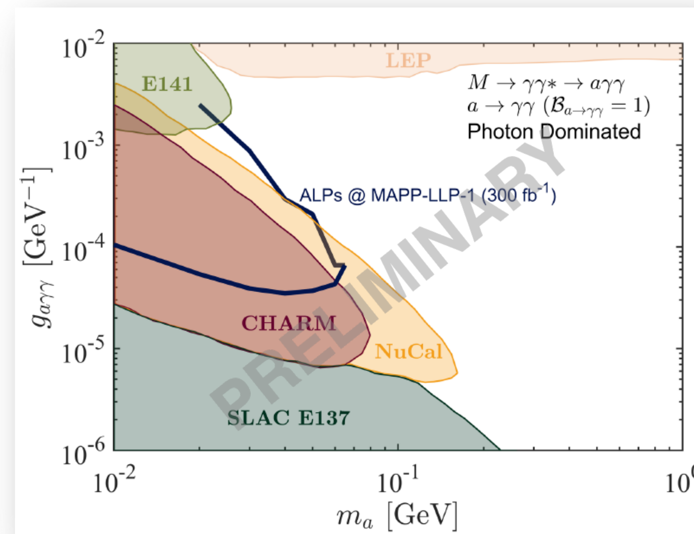
MAPP-LLP will explore **hidden sectors** in the **long-lifetime** regime

- dark photons
- dark Higgs bosons
- heavy neutral leptons
- **axions & ALPs**

For a review on LLP experiments, see: VAM, 2111.03036 [hep-ex]

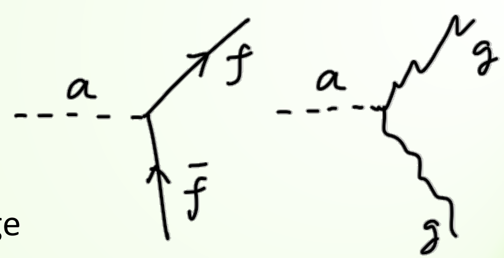
- Pseudoscalar portal: ALPs produced via rare decays of π and η mesons
- Light ALPs with mass of 10 MeV – 1 GeV with suppressed couplings can be long lived → detectable in MAPP-LLP

95% CL for ALPs @ √s = 14 Tev



Axion-like particles ("ALPs")

- solution of the strong CP problem
- generalisation of the axion model in MeV-GeV mass range

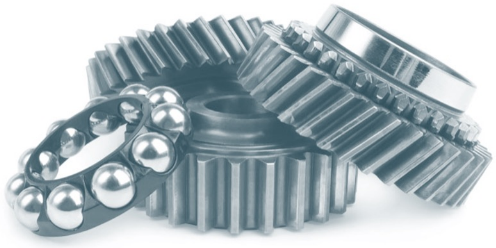


Summary & outlook

- Monopoles continue to excite interest and have been the subject of numerous experimental searches
- General-purpose experiments (**ATLAS**) and dedicated detectors (**MoEDAL**) provide *complementary* constraints in the quest for monopoles
  - ATLAS dominates *low* magnetic charges
  - MoEDAL is stronger in *high* charges
- Much higher charges can be probed by looking for trapped monopoles in beam pipes, e.g. CMS Run 1 beam pipe
- **MAPP** can further explore the low ionisation regime
  - mQP will probe ***extreme fractionally charged*** particles
    → millicharged particles
  - MAPP-2 with its LLP subdetector will search for neutral long-lived particles giving rise to displaced vertices
    - dark sectors, hidden valley models
    - axions and axion-like particles are among these particles

Thank you for your attention!

Spares



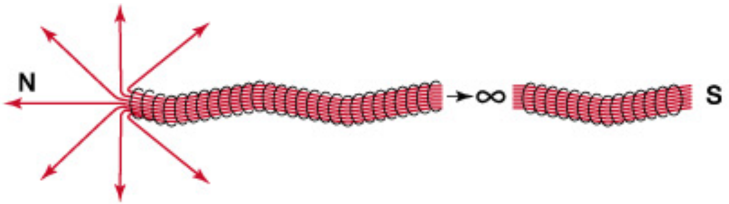
Magnetic monopoles

- 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:

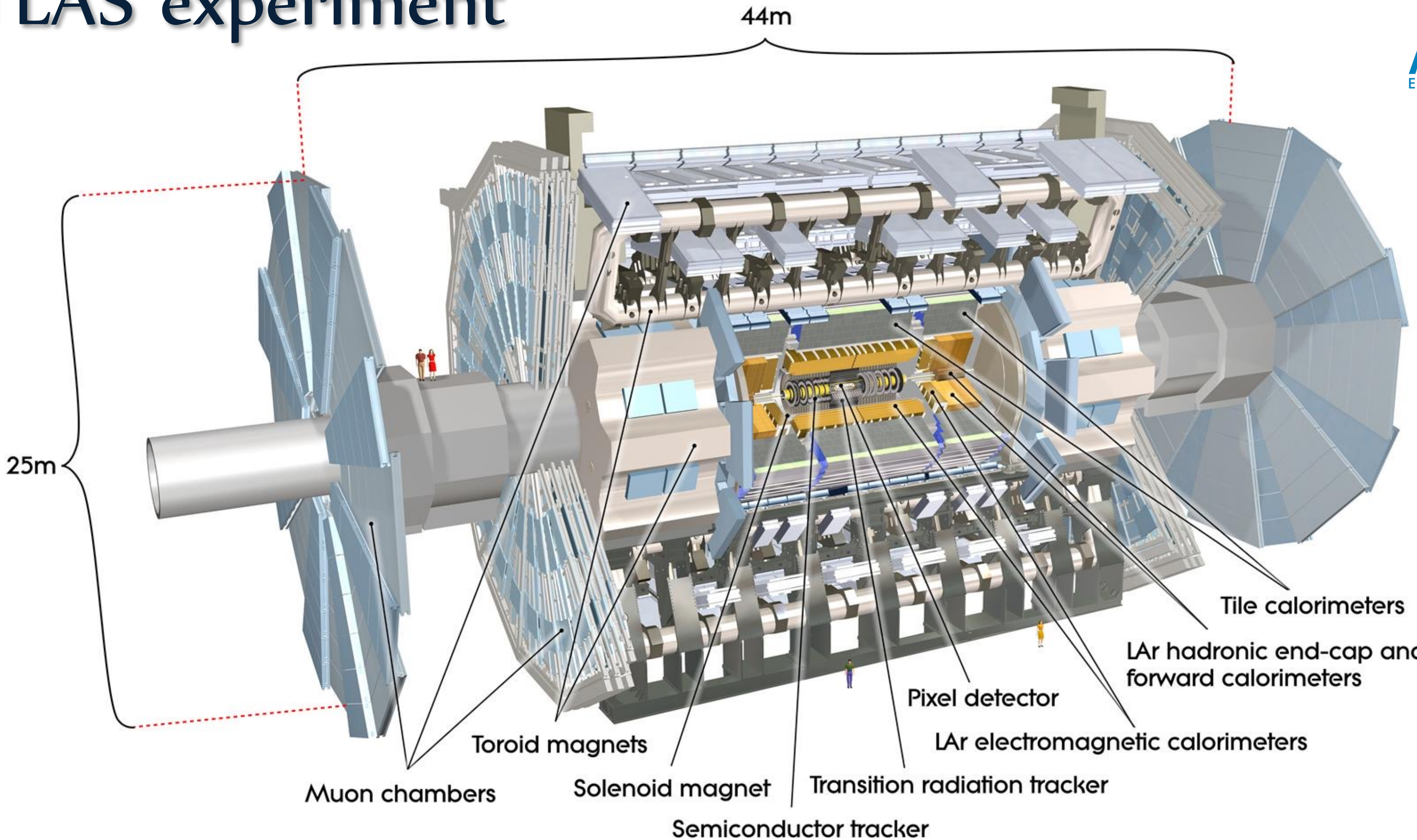
$$ge = n\left(\frac{\hbar c}{2}\right) \quad \text{OR} \quad g = \frac{n}{2\alpha}e = n g_D = n(68.5e)$$

- 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

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	$\nabla\times\mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$	$\nabla\times\mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$

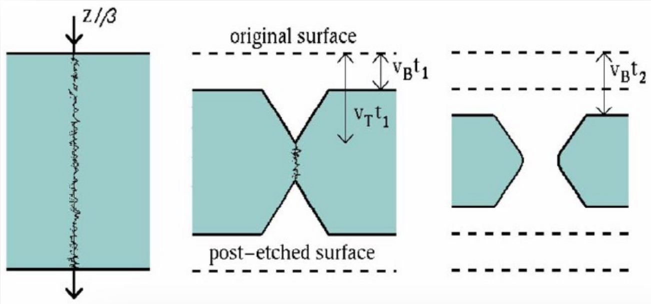


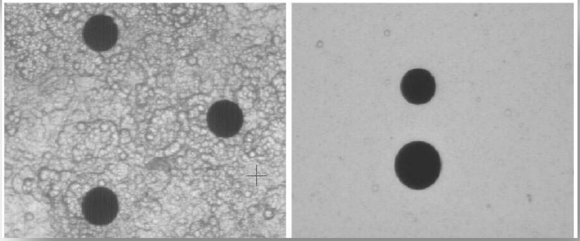
ATLAS experiment

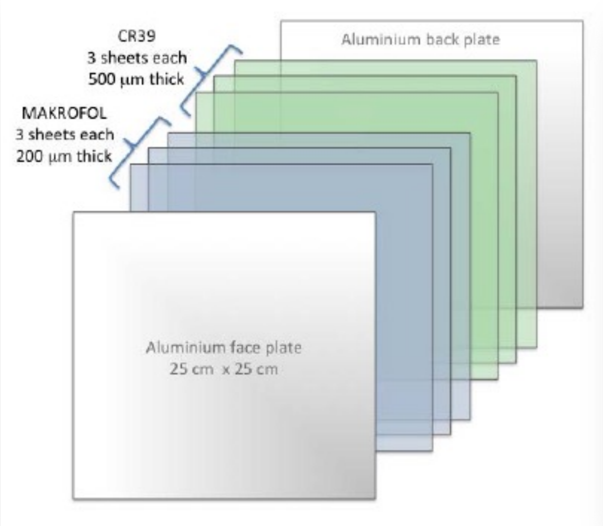


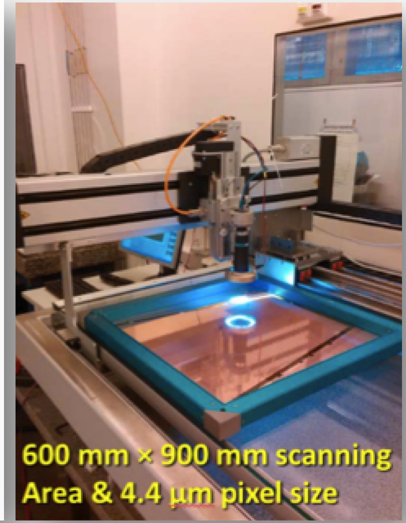
1 & 2 HI particle detection in NTDs

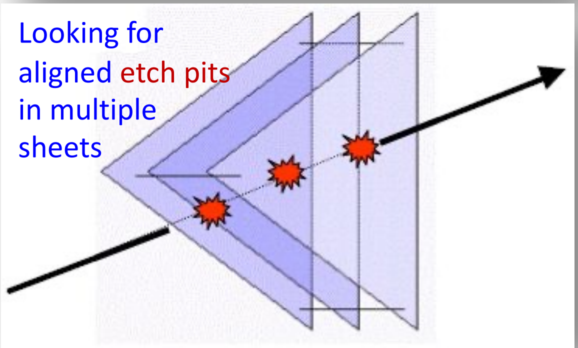
- Passage of a highly ionising particle through the plastic NTD marked by an invisible damage zone (**"latent track"**) along the trajectory
- The damage zone is revealed as a **cone-shaped etch-pit** when the plastic sheet is chemically **etched**
- Plastic sheets are later **scanned** to detect etch-pits





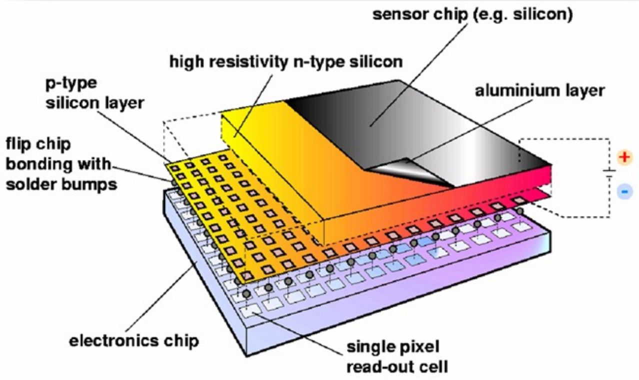


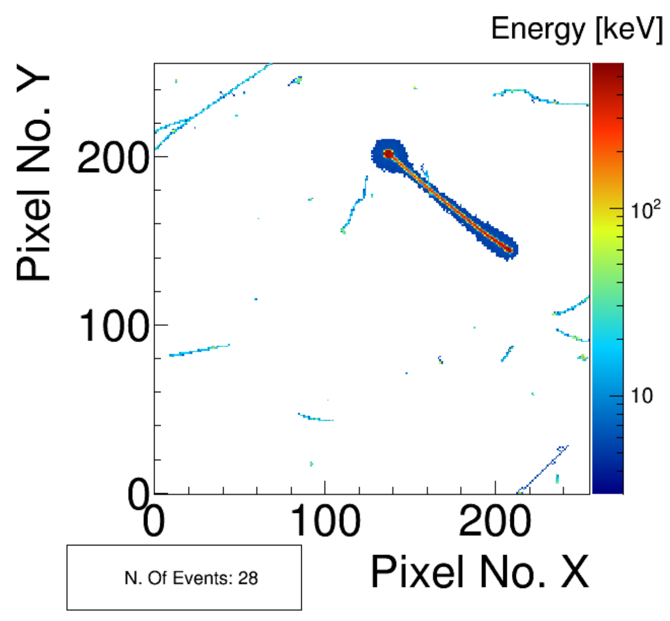




3 TimePix radiation monitor

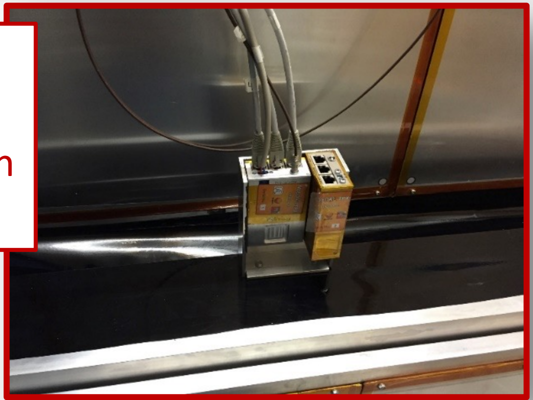
- Timepix (MediPix) chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic “bubble-chambers”
- The only active element in MoEDAL





Sample calibrated frame in MoEDAL TPX04

2015 deployment of MediPix chips in MoEDAL



- 256×256 pixel solid state detector
- 14×14 mm active area
- amplifier + comparator + counter + timer

Monopole/dyon results

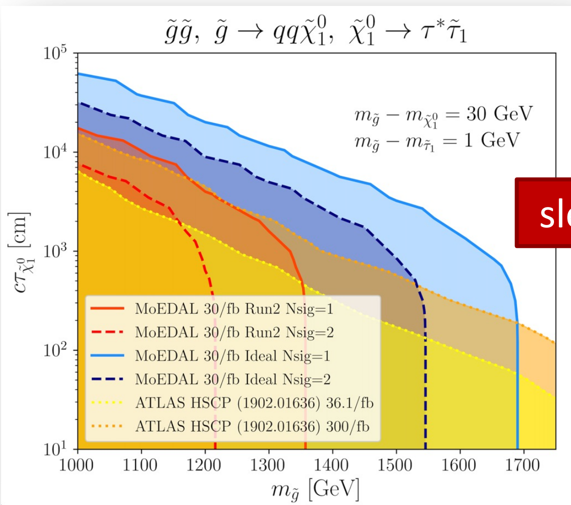
- **2016** – First results @ 8 TeV ☛ *CERN Press Release* JHEP 1608 (2016) 067 [arXiv:1604.06645]
- **2017** – First results **@ 13 TeV** Phys.Rev.Lett. 118 (2017) 061801 [arXiv:1611.06817]
- **2018** – MMT results Phys.Lett.B 782 (2018) 510–516 [arXiv:1712.09849]
  - **spin-1 monopoles**
  - β-dependent coupling
- **2019** – MMT results Phys.Rev.Lett. 123 (2019) 021802 [arXiv:1903.08491]
  - full MMT detector – ~4 times than previous
  - ~2 more integrated luminosity
  - **photon fusion interpretation (first time at LHC)**
- **2020** – First search for **Dyons** in colliders
  Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]
- **2021** – First search for production via the **Schwinger** mechanism
  arXiv:2106.11933

NEW

Electrically charged particles

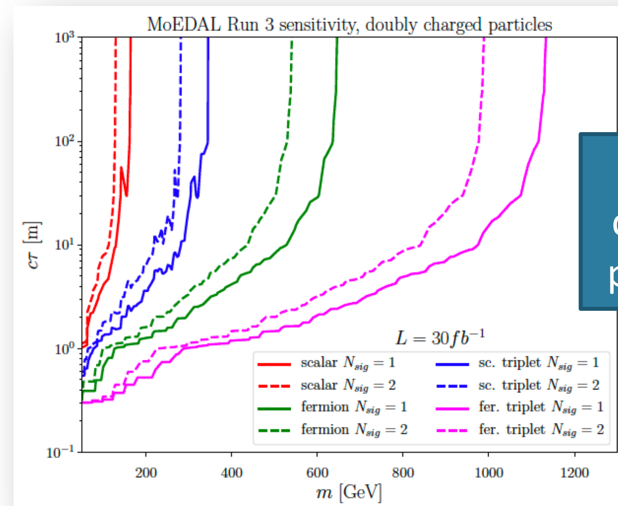
- If sufficiently slow moving, *singly* or *doubly* charged particles may leave a track in NTD
- Supersymmetry offers such long-lived states: **sleptons, R-hardons, charginos**
- Doubly charged scalars or fermions are predicted in type-II seesaw models of ν masses
- **MoEDAL can complement ATLAS/CMS reach in longer-lifetime region**

Felea et al, Eur.Phys.J.C 80 (2020) 431



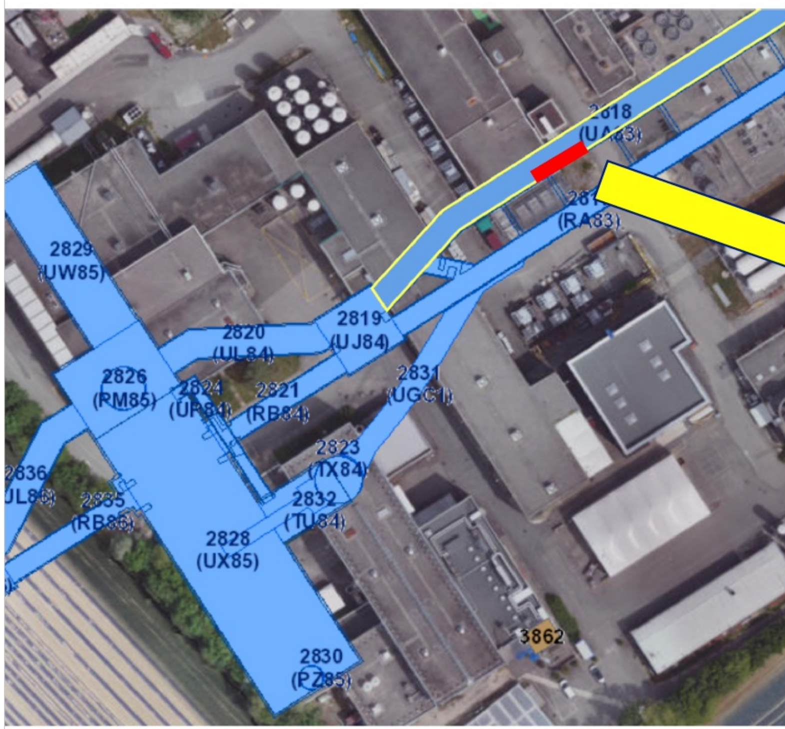
sleptons

Acharya et al, Eur.Phys.J.C 80 (2020) 572



doubly charged particles

Results on **Highly Electrically Charged Objects (HECOs)** in final stages of approval in MoEDAL
First MoEDAL analysis with NTDs !

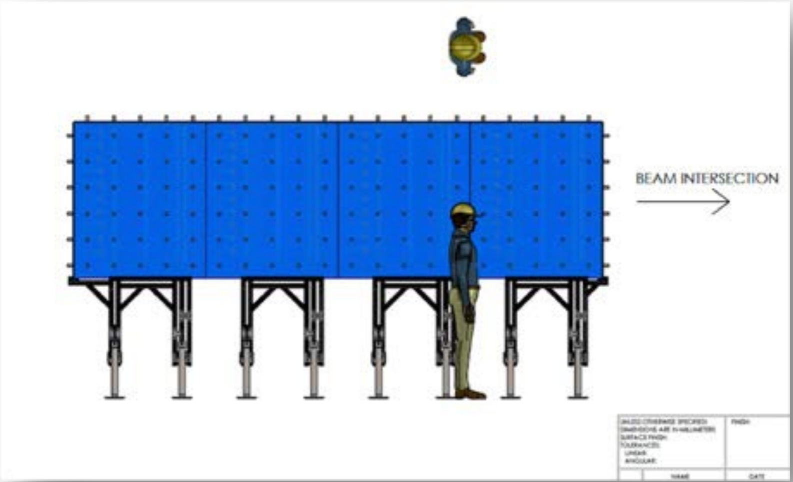

2829
(UW85)
2820
(UL84)
2819
(UJ84)
2826
(RM85)
2821
(RB84)
2831
(UGC1)
2823
(TX84)
2832
(TU84)
2828
(UX85)
2830
(PZ85)
3862
(RA83)

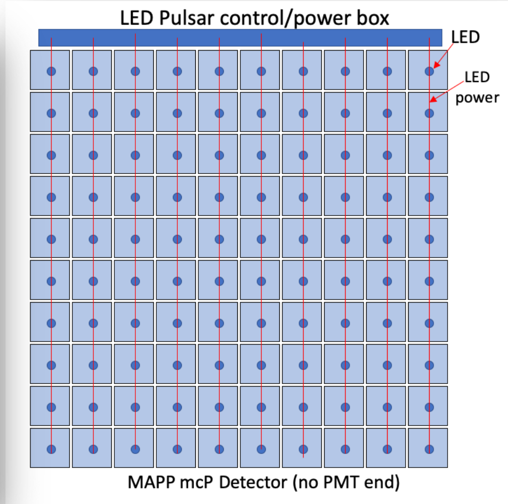

Rough Envelope of the
MoEDAL-MAPP-mQP
Detector in UA83

The MAPP-mQP detector

Prototype mQP installed in 2017
- 3×3 bars (~30×30 cm)
- ~10% of full detector

- Central milli-charged (mCP) detection sections
- Forward veto from SM particles coming from IP8
- 100 × (10 cm × 10 cm × 75 cm) scintillator bars in 4 lengths, 2 lengths/section readout by 4 low noise 3.1” PMTs in coincidence
- No background from dark counts and radiogenic backgrounds





Calibration by pulsed blue LEDs + neutral density filter

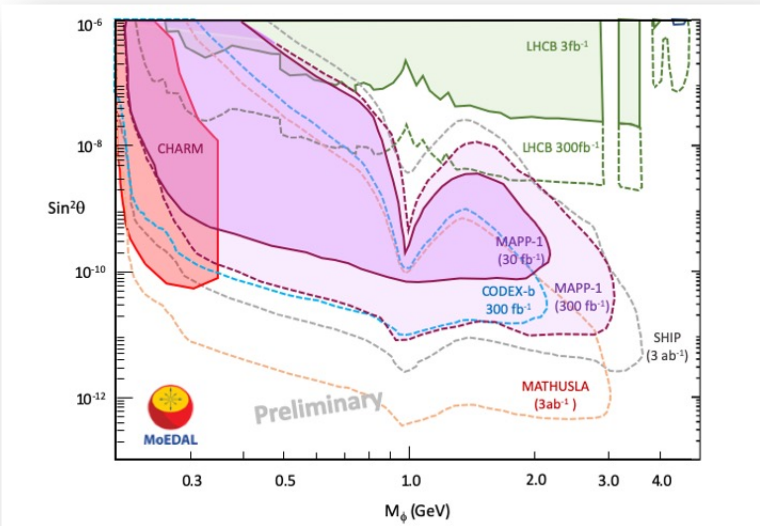
MAPP-mQP construction

MAPP/MALL preparation area

MAPP-mQP support structure being machined at the University of Alberta

MAPP-LLP projected physics sensitivity

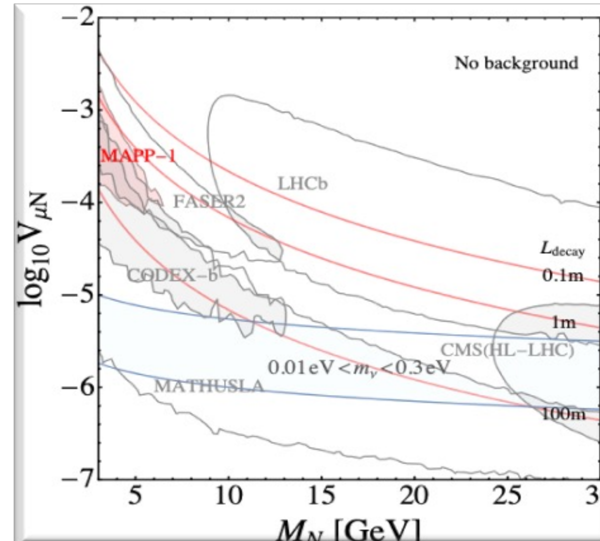
Dark Higgs scenario



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

Reach for 30 fb^{-1}/300 fb^{-1} for a scenario where a dark Higgs ϕ mixes with SM H^0 (mixing angle $\theta \ll 1$), leading to exotic $B \rightarrow X_s\phi$ decays with $\phi \rightarrow \ell^+\ell^-$

Heavy neutrino via Z' production



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

Pair production of RH neutrinos from the decay of an additional neutral Z' boson in the gauged B-L model – Run-3 (30 fb^{-1})

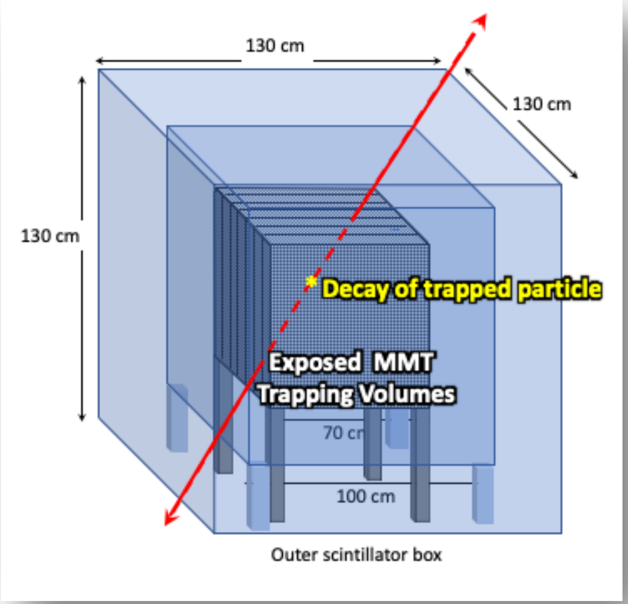
Promising physics reach for MAPP-LLP also for R-parity violating SUSY and sterile neutrino models [e.g. Dreiner et al, 2008.07539 & 2010.07305, respectively

MALL – MoEDAL Apparatus for very Long Lived particles

- After exposure and SQUID scan, MoEDAL MMTs will be monitored for decaying *electrically charged* particles possibly trapped in their volume

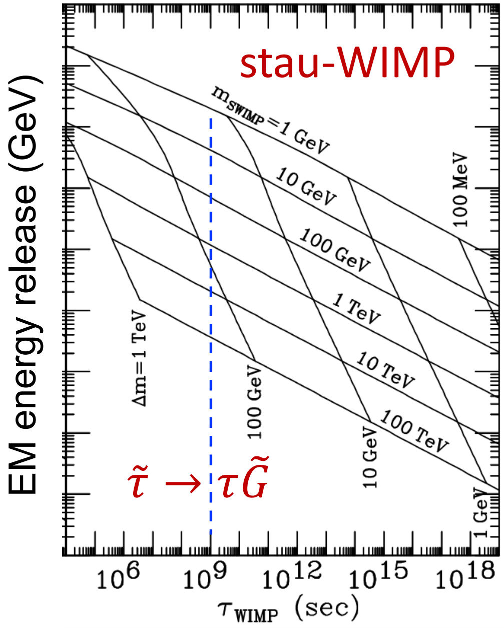
J. Pinfold, Universe 5 (2019) no.2, 47

- Sensitive to charged particles (e, μ, had.) and to photons with energy as small as 1~GeV
- Estimated MALL probed lifetimes **~10 yrs**
- MALL planned to be installed during Run-3 at the UGC1 gallery of IP8



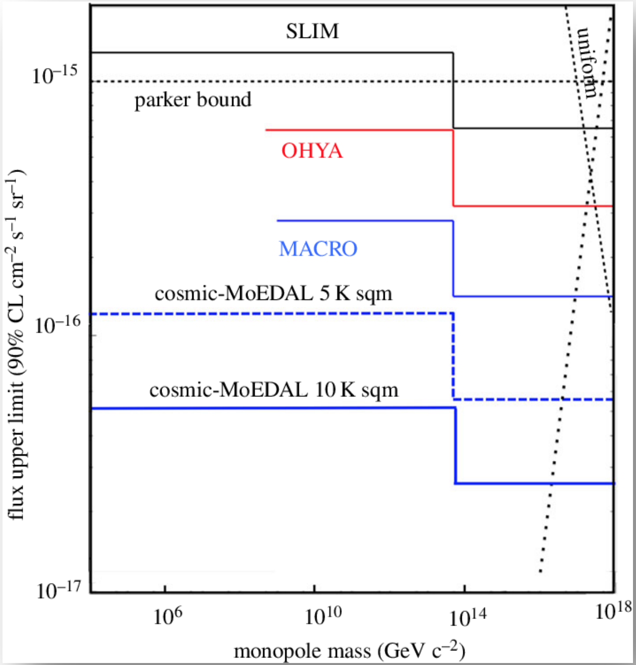
- **SuperWIMP model for cold dark matter, WIMP → SM + SWIMP**
- SuperWIMP particles may explain the observed lithium under-abundance
- For example, the lifetime of a ~150 GeV stau (WIMP) decaying to a ~100 GeV gravitino (SWIMP) is $\mathcal{O}(10^9\text{ s})$ i.e. $\mathcal{O}(10\text{ yr})$

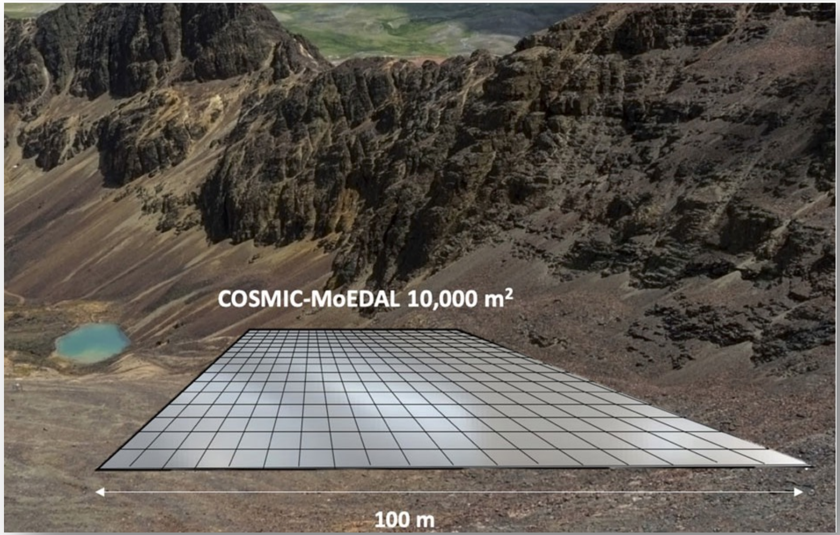
Feng, Rajaraman, Takayama, Phys. Rev. D 68, 063504 (2003)



Cosmic-MoEDAL

- If magnetic monopoles are much heavier than $\mathcal{O}$(TeV), they could be detected in "monopole telescopes"
- "Cosmic-MoEDAL" is a proposal for a very large array (~10,000 m²) of CR-39 NTDs to be deployed at very high altitude, e.g. at Mt Chacaltaya laboratory in Bolivia (5,400 m)





Able to search for cosmic monopoles with velocities β ~ 0.1, from the LHC's TeV scale all the way to the GUT scale

J. L. Pinfold, arXiv:1412.8677 & Phil.Trans.Roy.Soc.Lond.A 377 (2019) 2161, 20190382