MoEDAL, MAPP and future endeavours

DISCRETE 2020-2021 Bergen Nov 29 – Dec 3 2021

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for the MoEDAL Collaboration

MoEDAL – Monopole & Exotics Detector At LHC

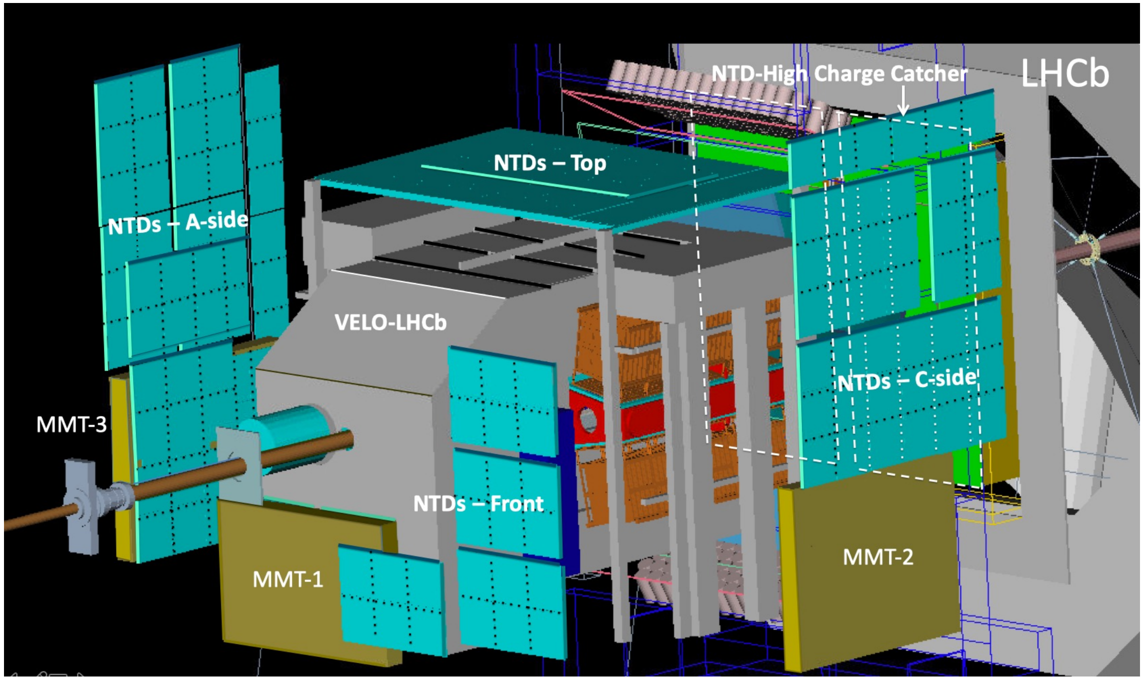
LHC's first dedicated *search* experiment
(approved 2010)

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



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

MoEDAL

DETECTOR SYSTEMS

① Low-threshold NTD (**LT-NTD**) array
  - $z/\beta > \sim 5\text{-}10$

② Very High Charge Catcher NTD (**HCC-NTD**) array
  - $z/\beta > \sim 50$

③ **TimePix** radiation background monitor

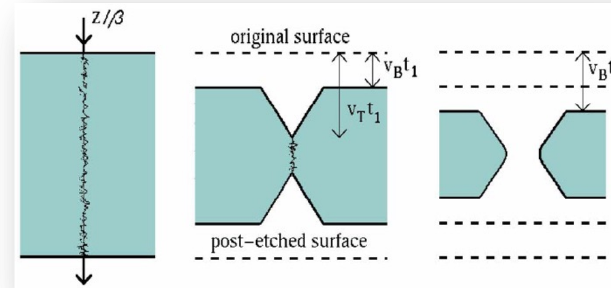
④ Monopole Trapping detector (**MMT**) – aluminum bars

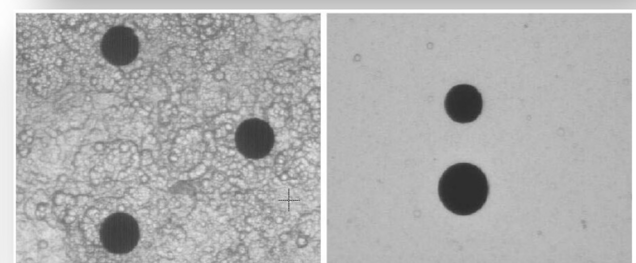
MoEDAL physics program

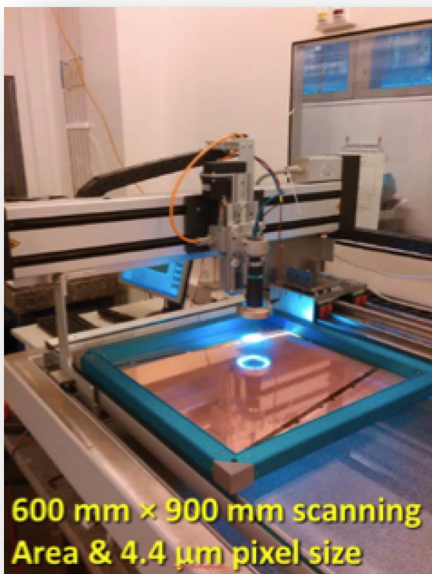
[Int. J. Mod. Phys. A29 (2014) 1430050]

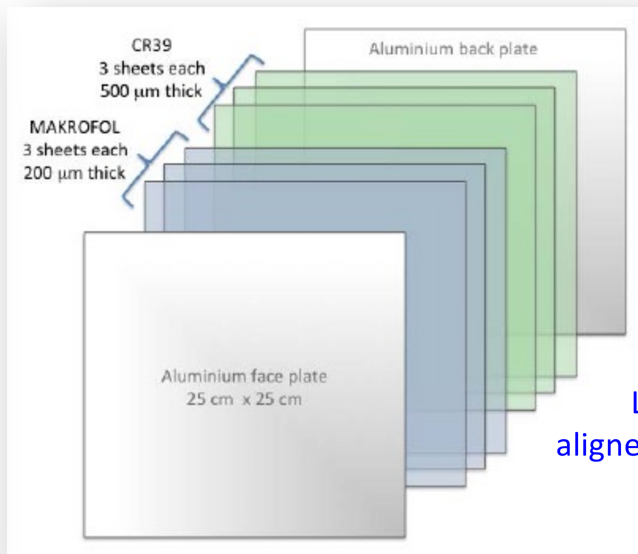
Nuclear Track Detectors (NTDs)

- 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

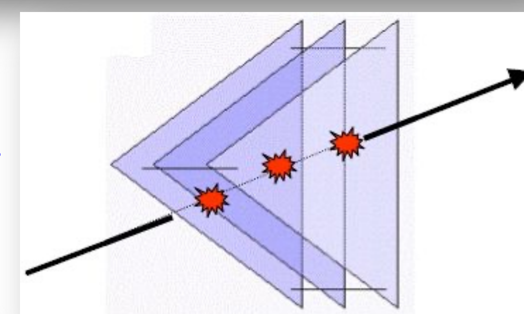








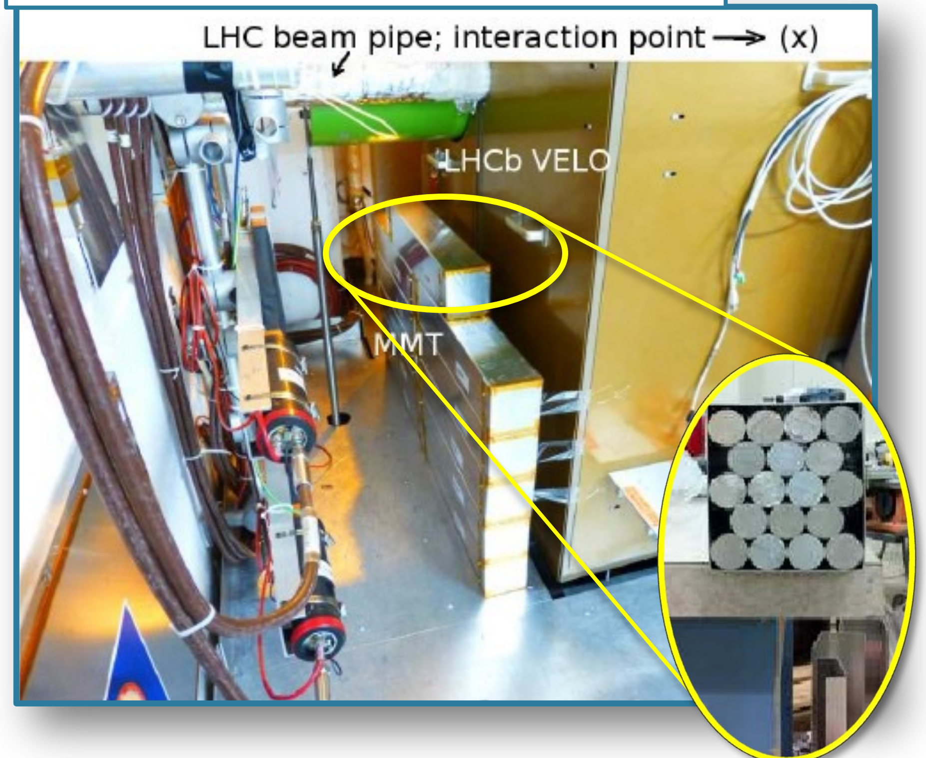
Looking for aligned etch pits in multiple sheets



MMTs deployment

MoEDAL

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



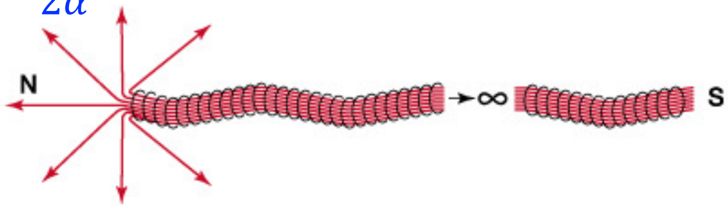
2015-2018

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

Magnetic monopoles

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

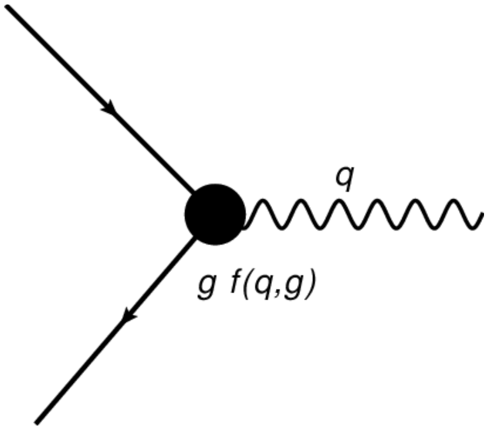
- Symmetrise Maxwell's equations
  - electric ↔ magnetic charge duality
- **Paul Dirac** in 1931 hypothesised that the magnetic monopole exists
  - monopole is the end of an infinitely long and infinitely thin solenoid *(Dirac's string)*
  - Dirac's quantisation condition: $ge = n\left(\frac{\hbar c}{2}\right)$ OR $g = \frac{n}{2\alpha}e = ng_D = n(68.5e)$



- 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
- **Yongmin Cho** proposed in 1986 the **Electroweak (Cho-Maison) 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 by MoEDAL at LHC!**

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

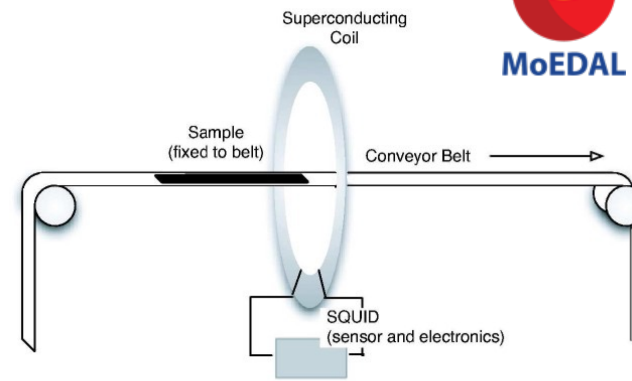
Monopole properties in a nutshell



- 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, $\beta = \sqrt{1 - \frac{4M^2}{s}}$
- 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**

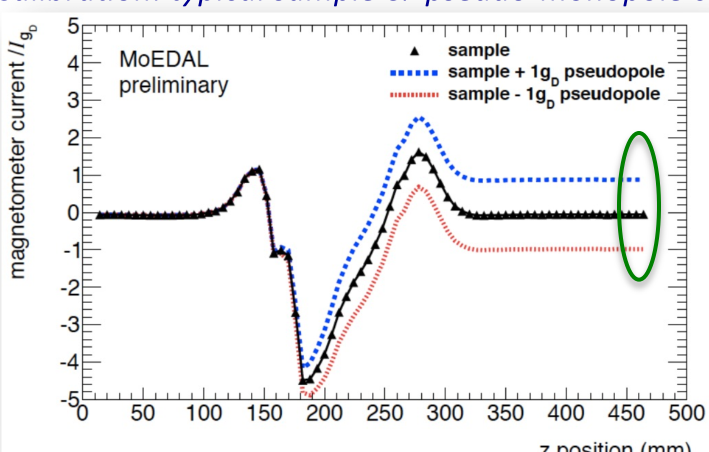
Induction technique results

- 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



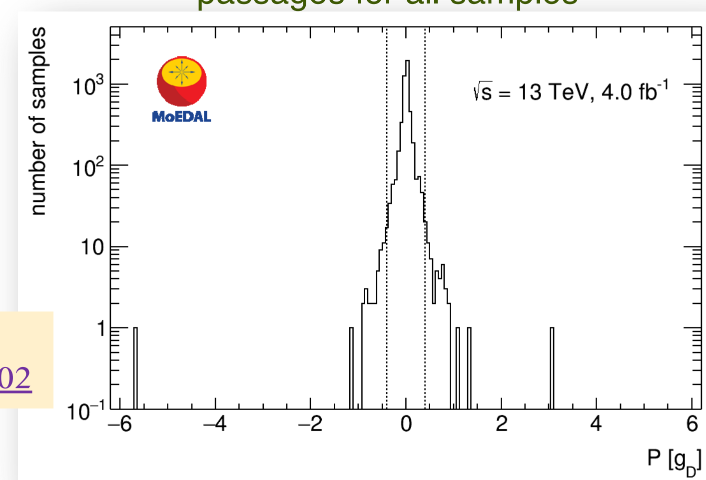
MoEDAL

Calibration: typical sample & pseudo-monopole curves



MoEDAL, PRL 123 (2019) 021802

Persistent current after first two passages for all samples

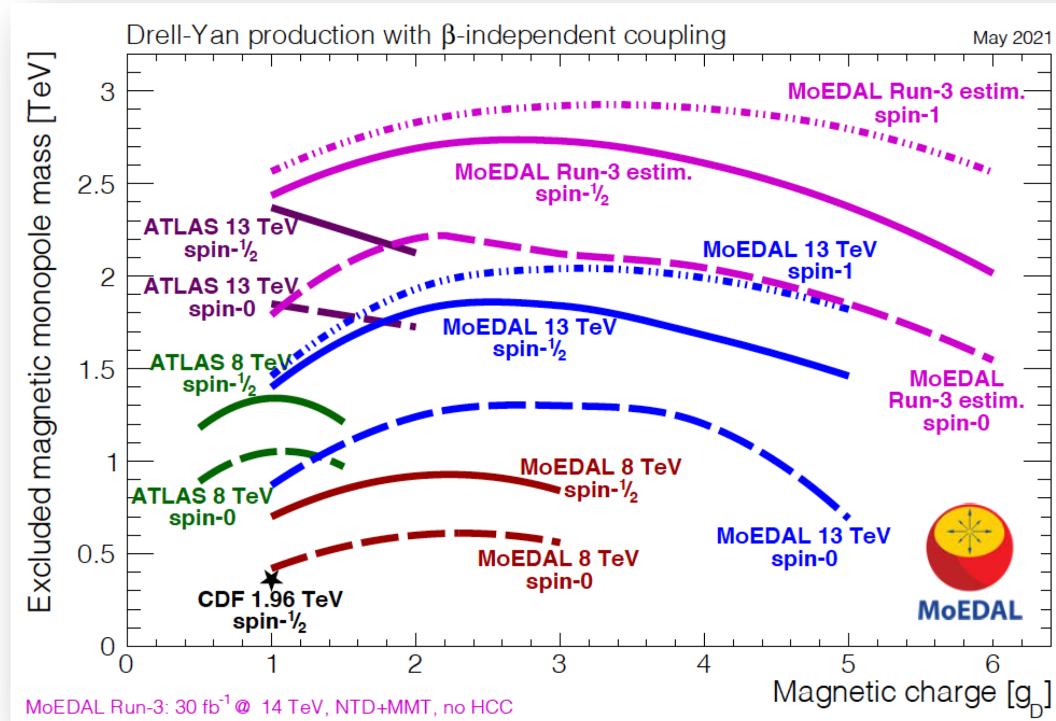


Magnetic monopole limits

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

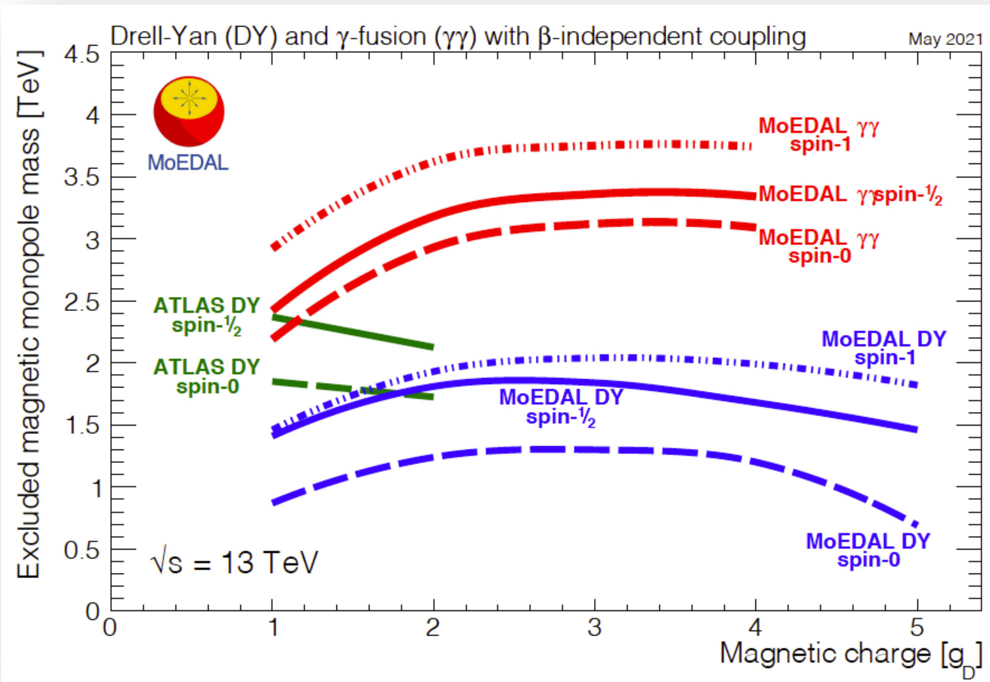
- β-dependent coupling
- spin-1 monopoles
- γγ fusion

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



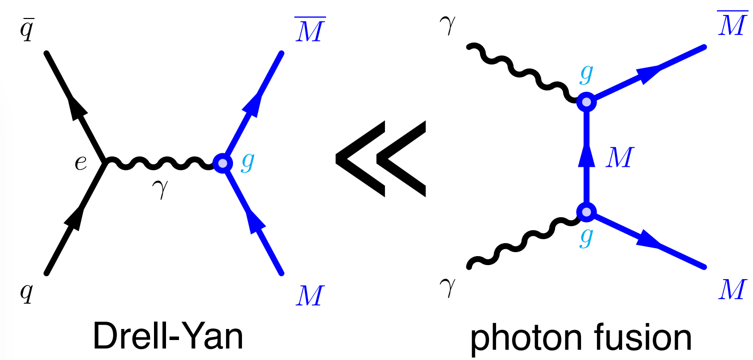
MoEDAL, JHEP 1608 (2016) 067, PRL 118 (2017) 061801, PLB 782 (2018) 510, PRL 123 (2019) 021802

Drell-Yan & γγ-fusion



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

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



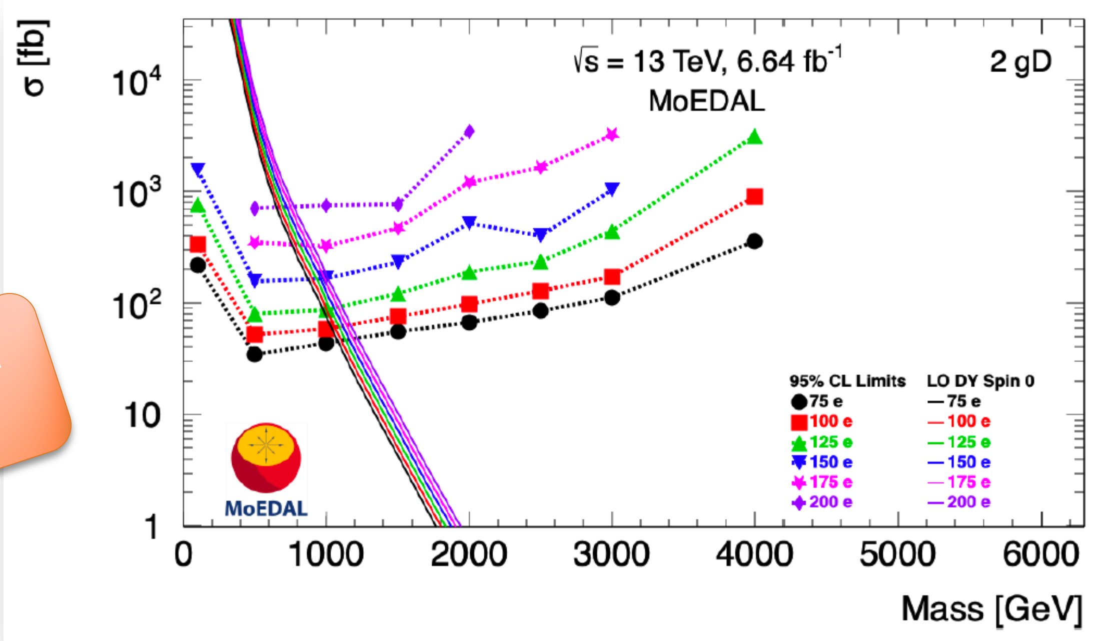
Photon-fusion monopole production process has much higher cross section than Drell-Yan-like at the LHC c.m.s. energies

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

Search for dyons

- 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**

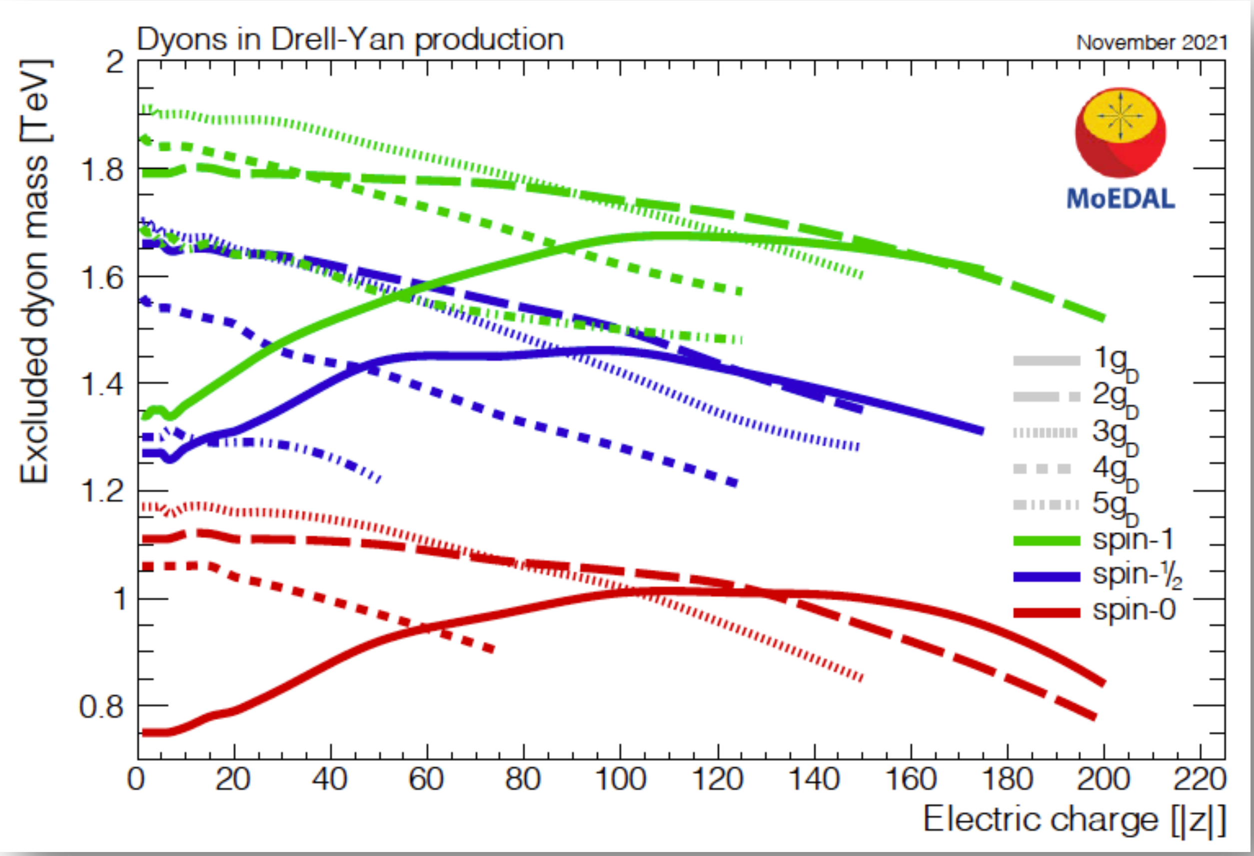
MoEDAL, Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]



First explicit accelerator search for direct dyon production!

Search for dyons – results

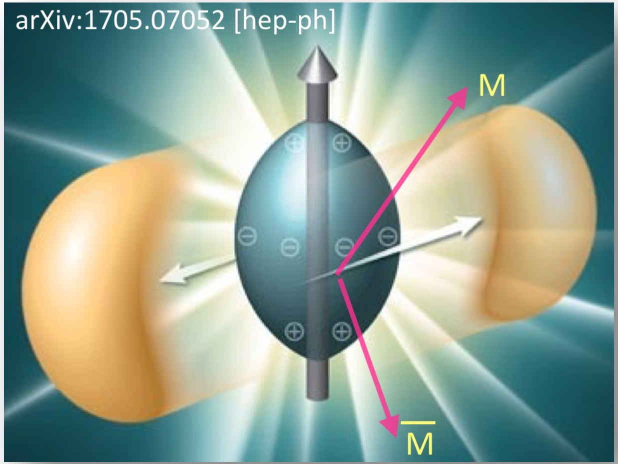
- Mass limits **750-1910 GeV** were set for dyons with
  - up to 5 Dirac magnetic charges (**5g_D**)
  - electric charge **1e – 200e**
- Previous searches for highly ionising particles would, in principle, also have sensitivity to dyons

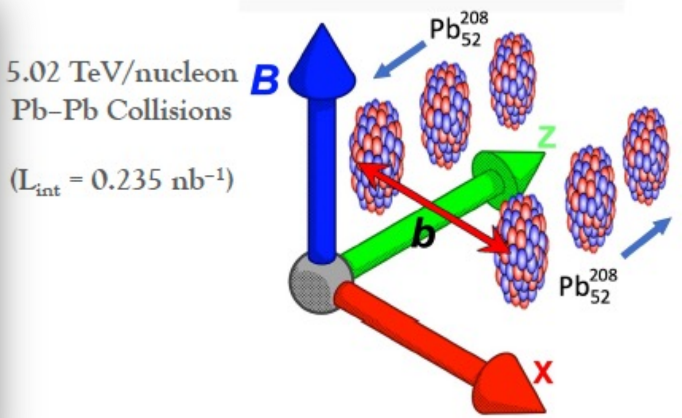


MoEDAL, Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]

Monopoles via thermal Schwinger mechanism

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





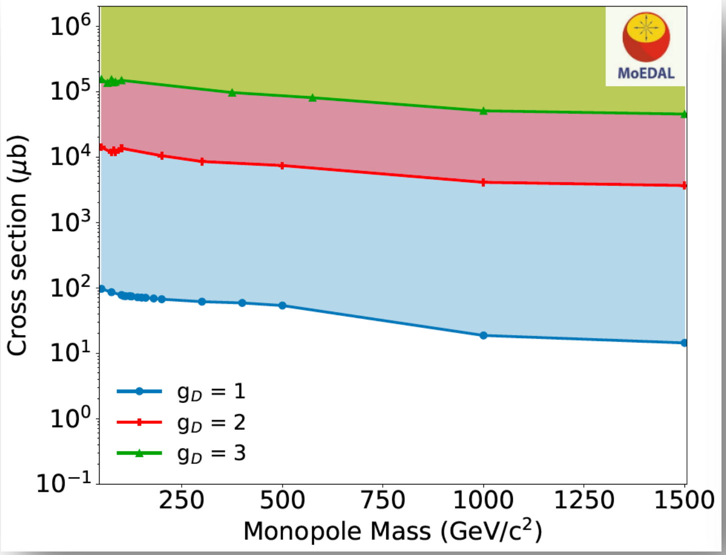
Advantages over DY & γγ-fusion production

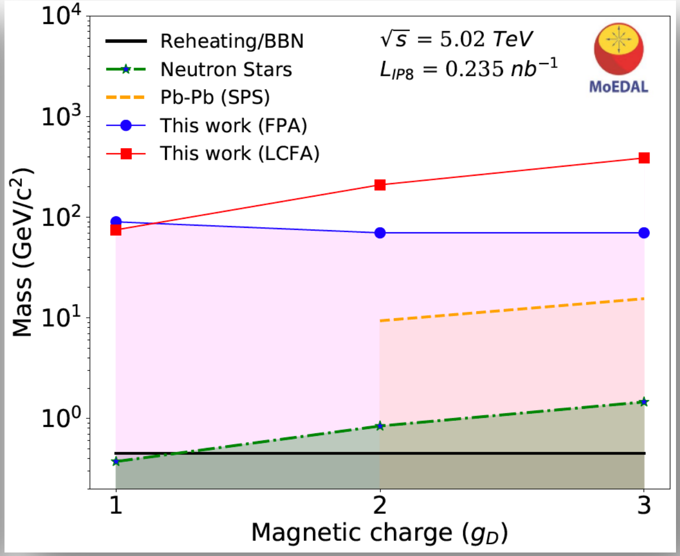
- cross-section calculation using semiclassical techniques
  ⇒ does not suffer from non-perturbative nature of coupling
- no exponential suppression $e^{-4/\alpha}$ for finite-sized monopoles

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

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

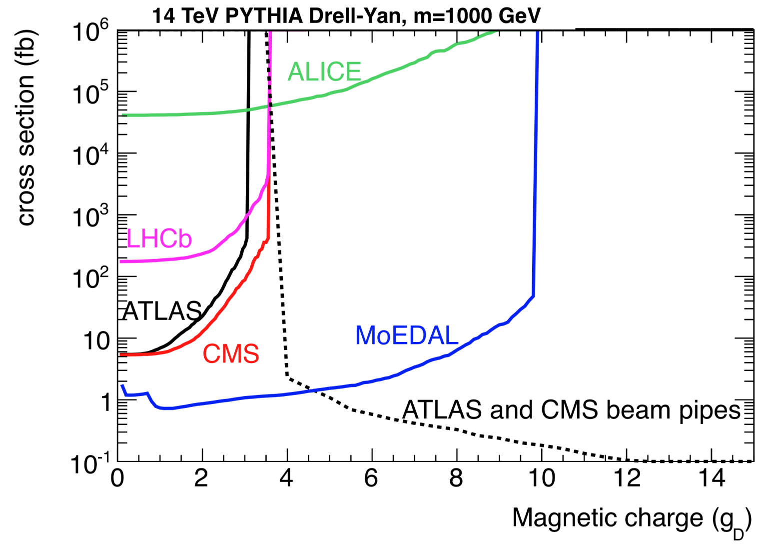
MoEDAL, arXiv:2106.11933, submitted to *Nature*

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

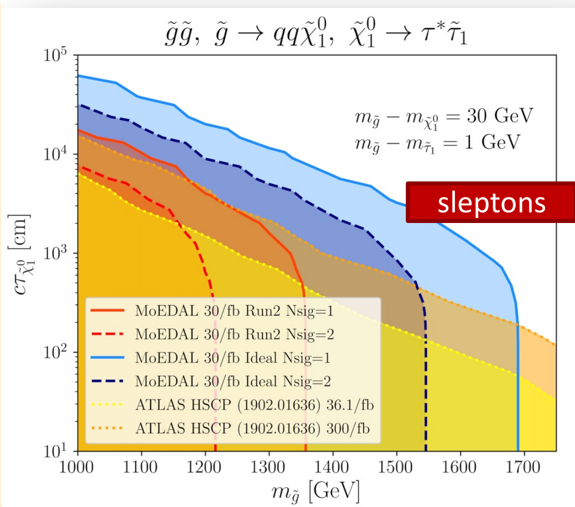
CERN Courier, Mar-Apr 2019

Electrically charged particles

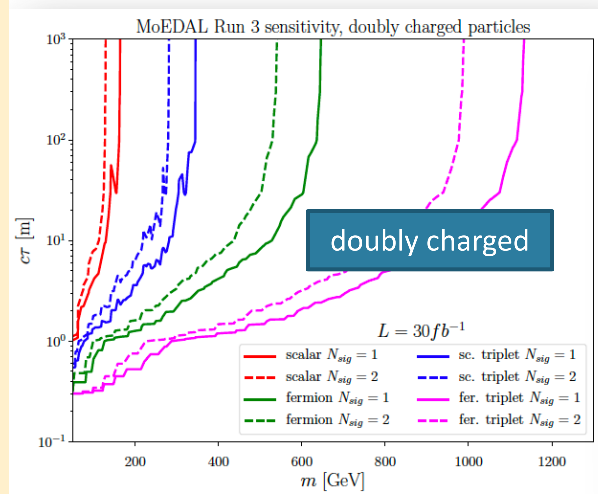
☛ *Thursday talk by Rafal Maselek*

- If sufficiently slow moving, *singly* or *multiply* charged particles may leave a track in NTD
- Supersymmetry offers such long-lived states: **sleptons, R-hardons, charginos**
- Multiply charged scalars or fermions are predicted in several models of ν masses
- Highly Electrically Charged Objects (HECOs): finite-sized objects (Q-balls), condensed states (strangelets), microscopic black holes (though their remnants)
- **MoEDAL can complement ATLAS/CMS reach in longer-lifetime region**

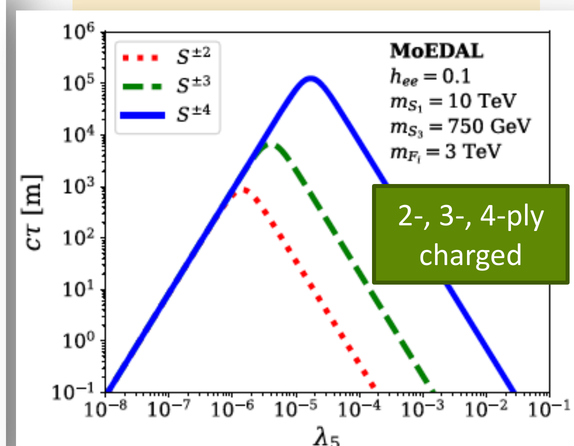
Felea, VAM et al, EPJC 80 (2020) 431



Acharya et al, EPJC 80 (2020) 572

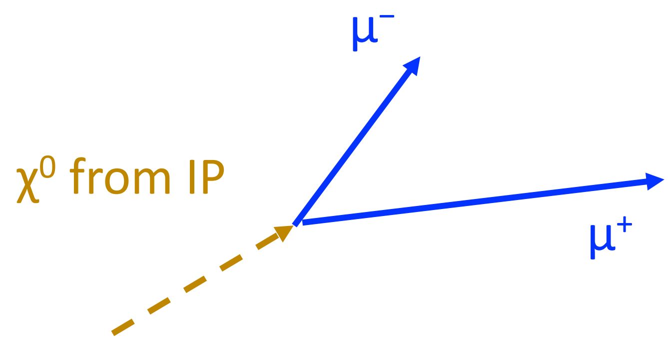


Hirsch et al, EPJC 81 (2021) 697



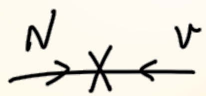
Results on **HECOs** in final stages of approval ☛ First MoEDAL analysis with **NTDs** !

MoEDAL MAPP

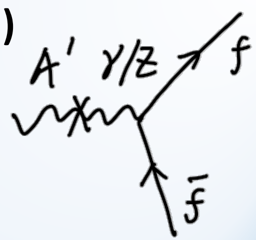


Hidden sector & long-lived particles

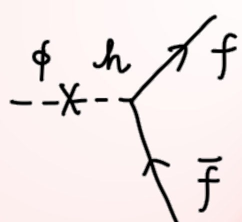
Heavy neutral leptons ("sterile neutrinos")
- explain SM ν masses (seesaw), DM, BAU
- weak semi-leptonic decays of hadrons, W, Z



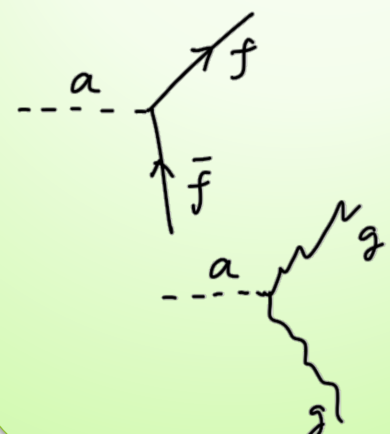
Dark vectors ("Dark Photons")
- adding U(1) gauge group to SM, kinetic mixing with γ/Z
- light neutral meson decays, milli-charged particles

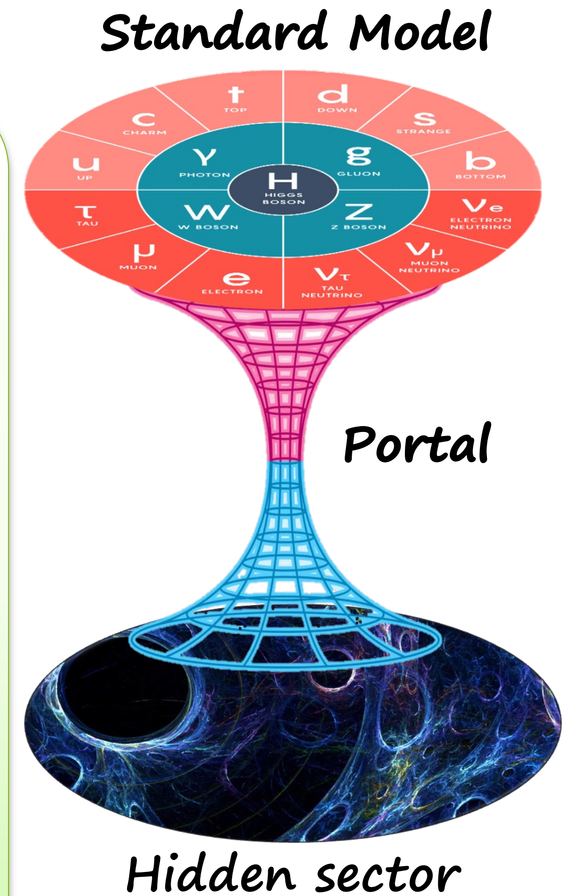


Dark scalars ("Dark Higgs")
- neutral singlet scalers that couple to the SM Higgs field
- produced in penguin decays of K, D, B mesons



Axion-like particles ("ALPs")
- solution of the strong CP problem
- generalisation of the axion model in MeV-GeV mass range





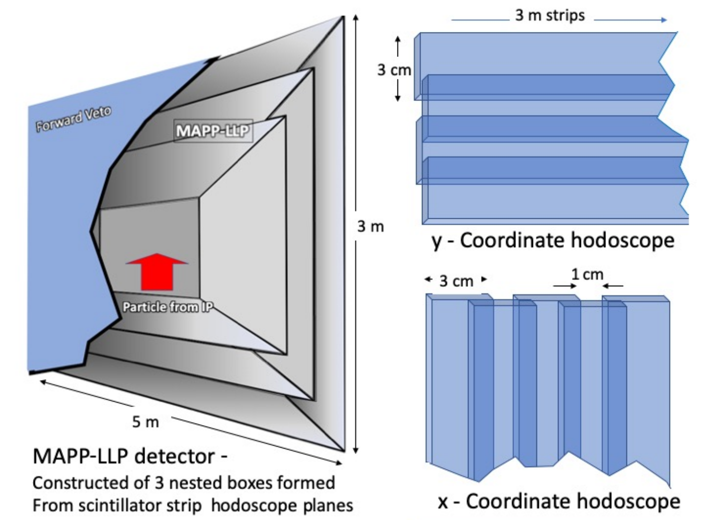
For a review on LLP experiments, see: VAM, 2111.03036 [hep-ex]

MAPP – MoEDAL Apparatus for Penetrating Particles

Consists of two subdetectors:

- core millicharged particle detector **MAPP-mQP**
  - particles with charges $\ll 1e$ 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

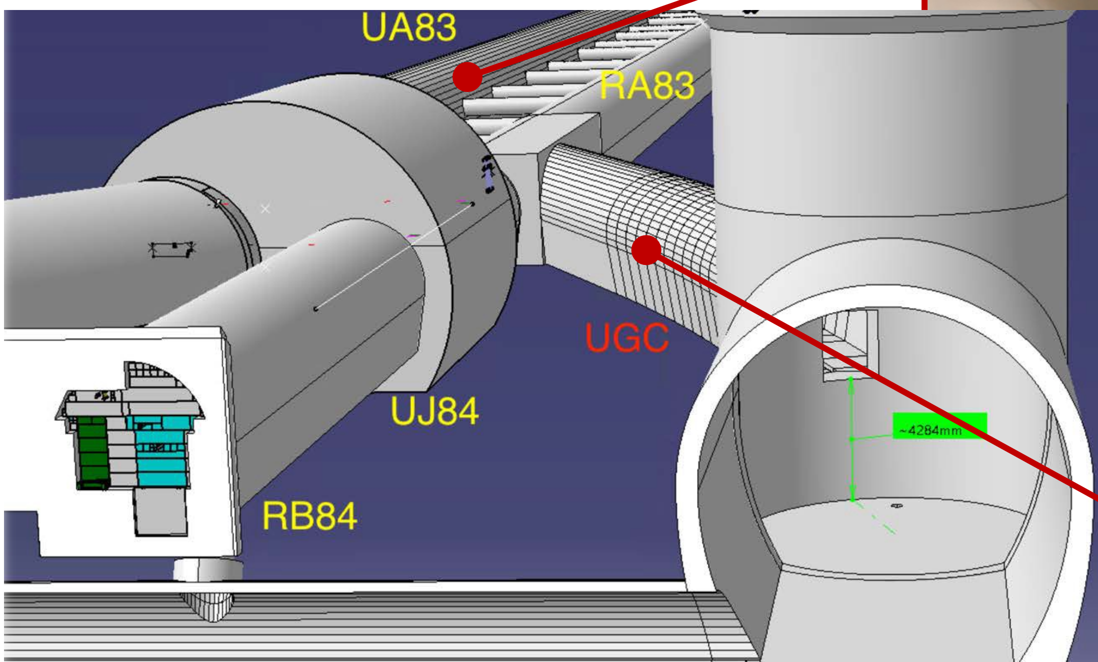
- 3×3 bars (~30×30 cm)
- ~10% of full detector

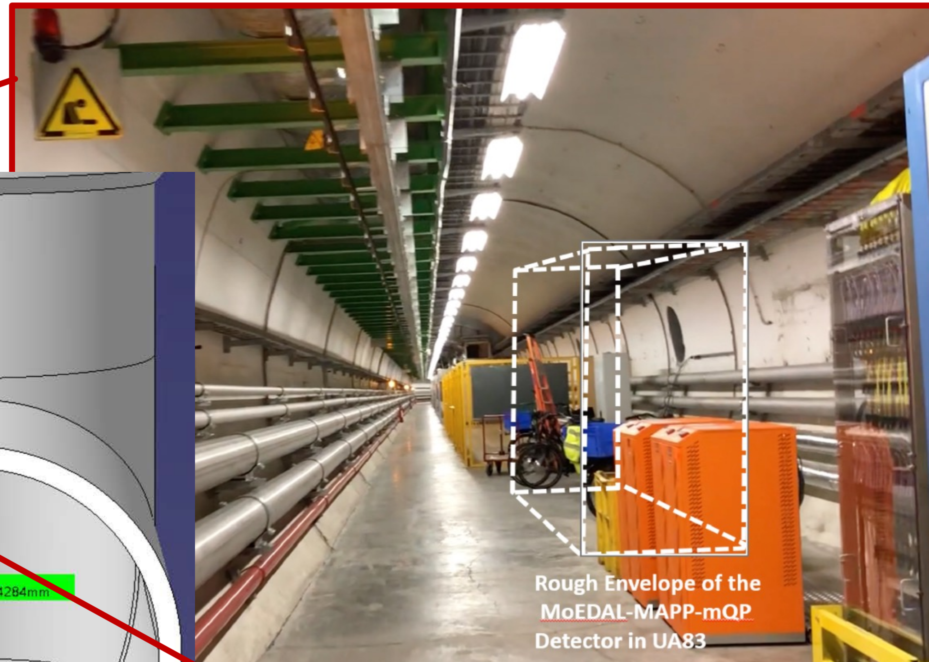
MAPP approved by CERN Research Board on Dec 1st 2021 !

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

MAPP possible location in UA83

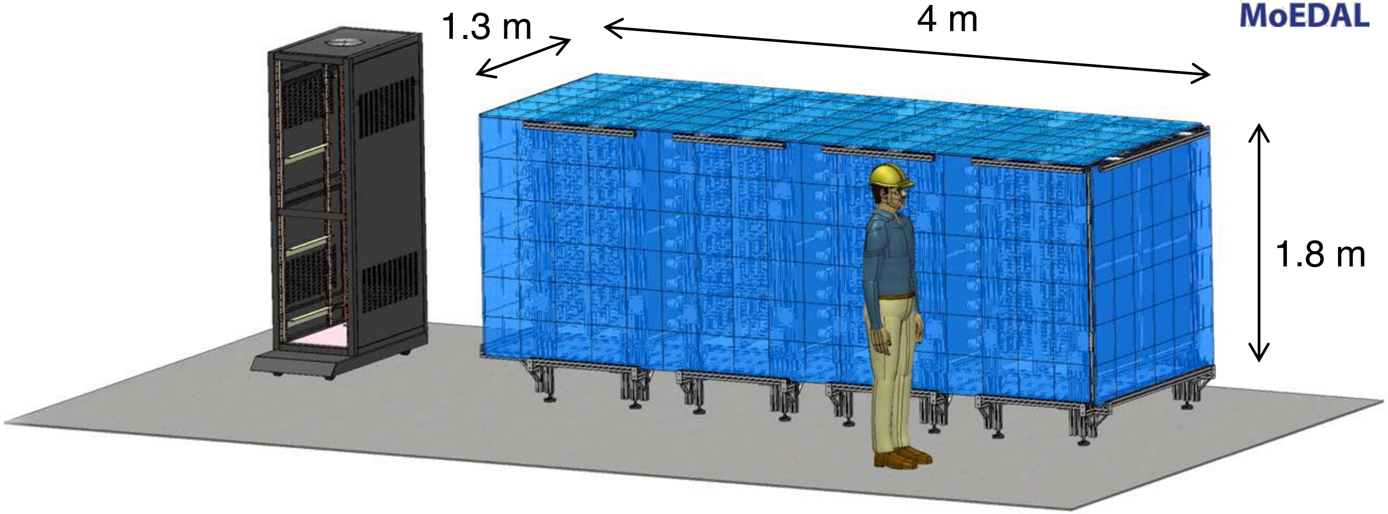
- Easily accessible gallery, already fitted out
- Access independent from LHCb





previous position
(mQP 2017 prototype)

MAPP-mQP detector

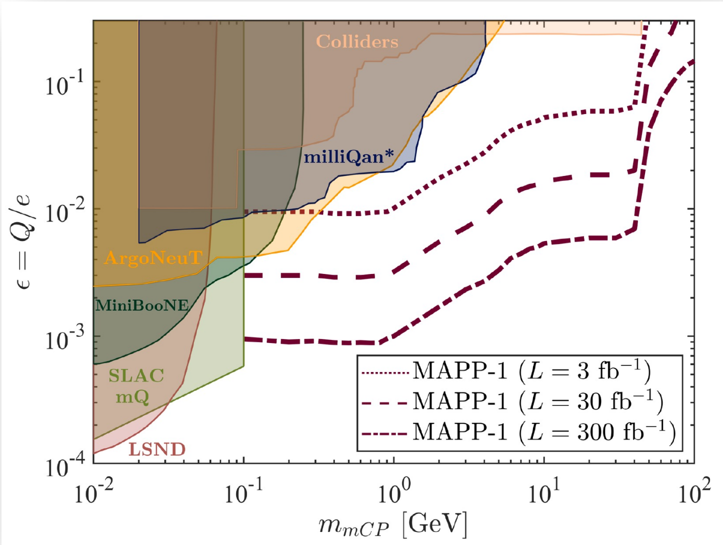


complete section

- Consists of 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
- Deployed in UA83 for Run-3 → **100 m** 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
- Installation planned to start in December 2021

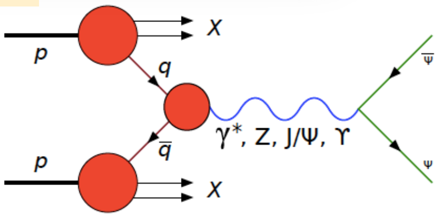
mQP & millicharged particles (mCPs)

Dark photon decays to mCPs

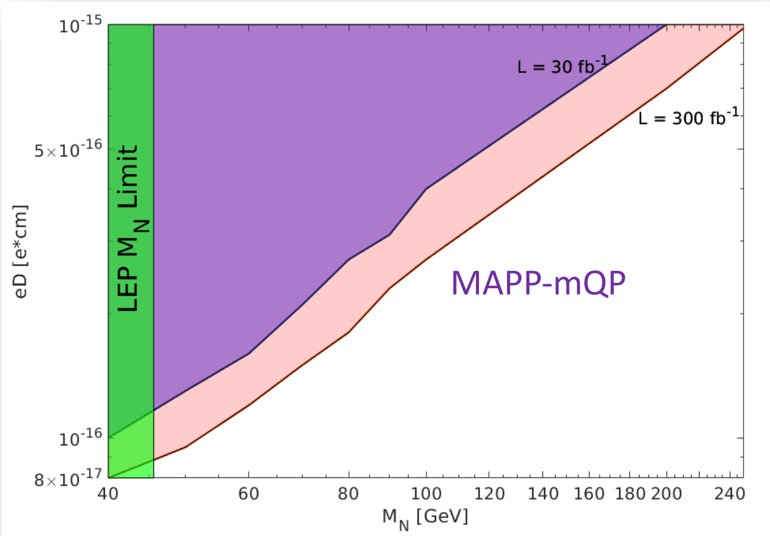


M. Staelens, PhD thesis, U. Alberta

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



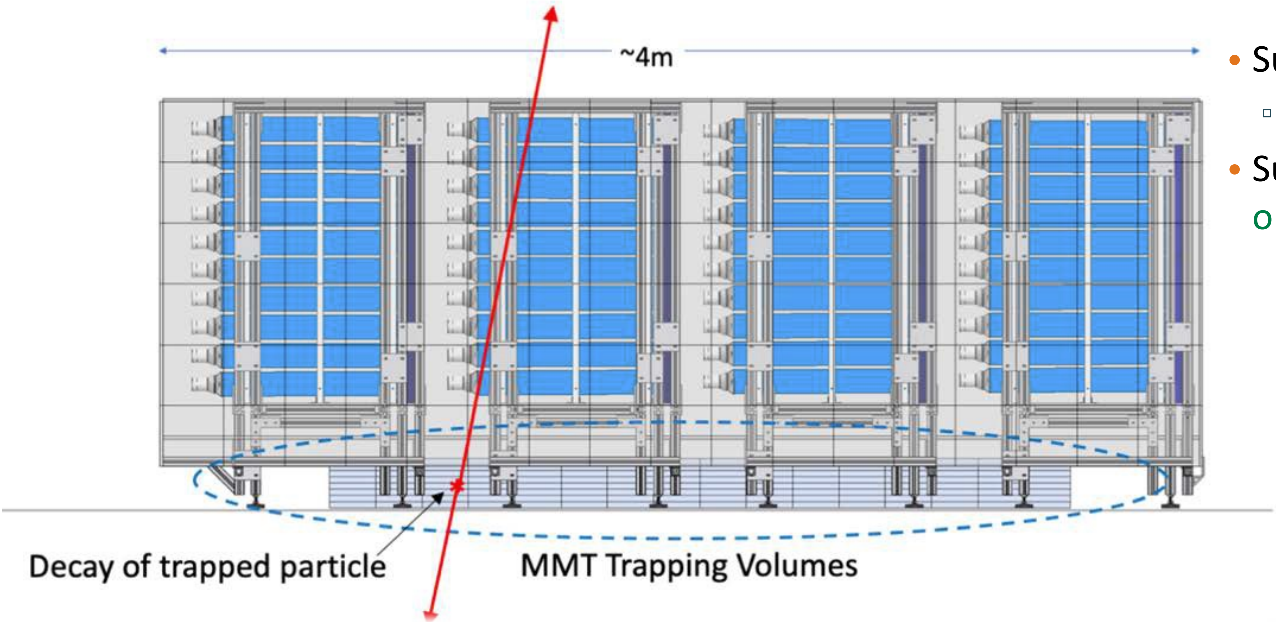
Heavy neutrino with large EDM



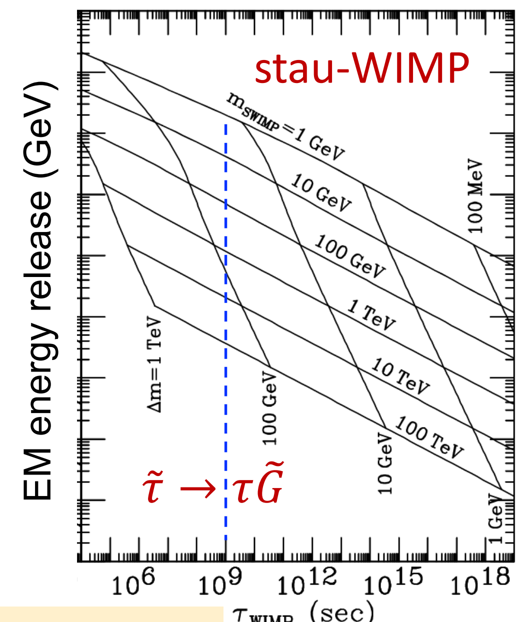
Frank et al, Phys.Lett.B 802 (2020) 135204

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

Extremely Long-Lived Charged Particles with MAPP-mQP



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

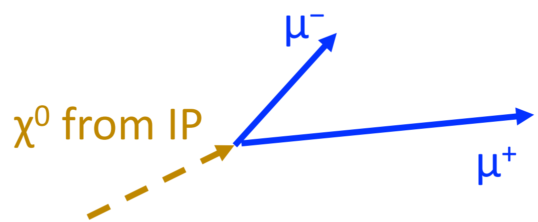


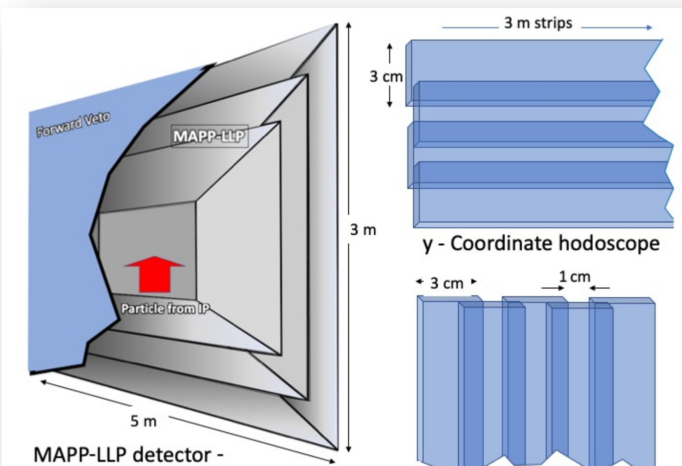
- MAPP-mQP can be used to monitor MoEDAL's exposed trapping detector for the decays of electrically charged trapped particles
  - exposed trapping volumes moved directly underground to UA83
  - lifetimes longer than 10 years can be probed

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

MAPP Phase 2 – LLP detector

- "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





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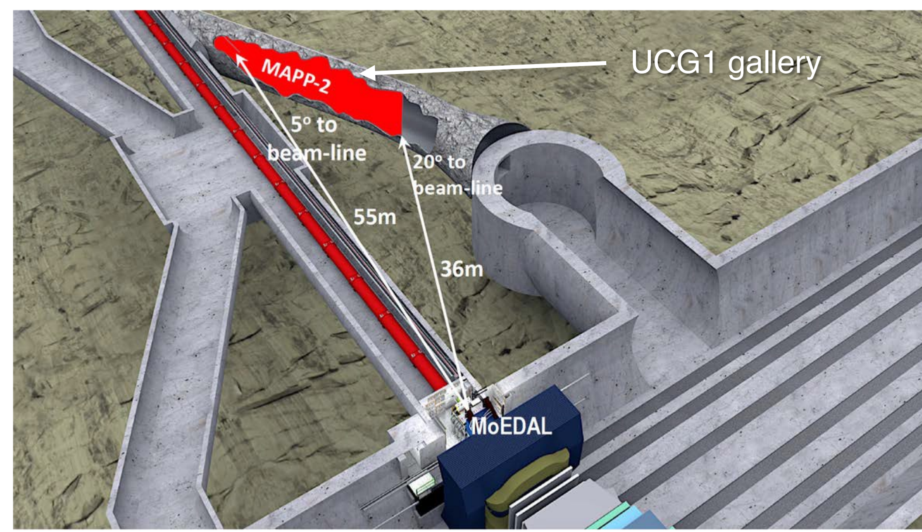
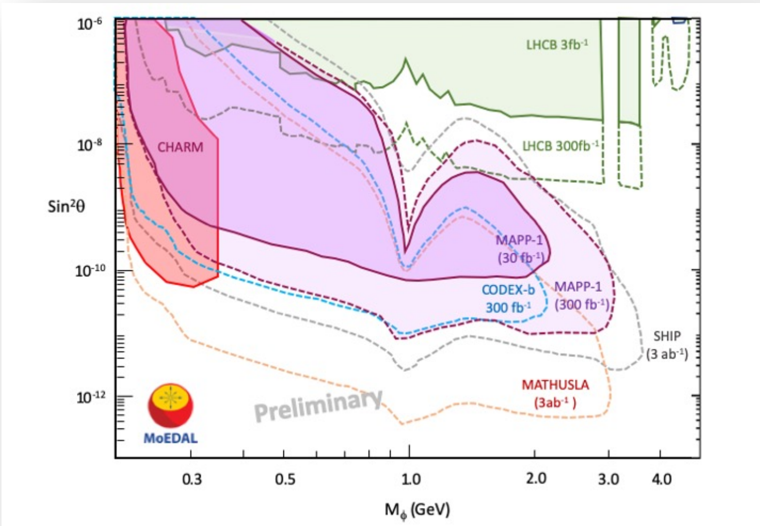


MAPP-LLP – dark matter & supersymmetry

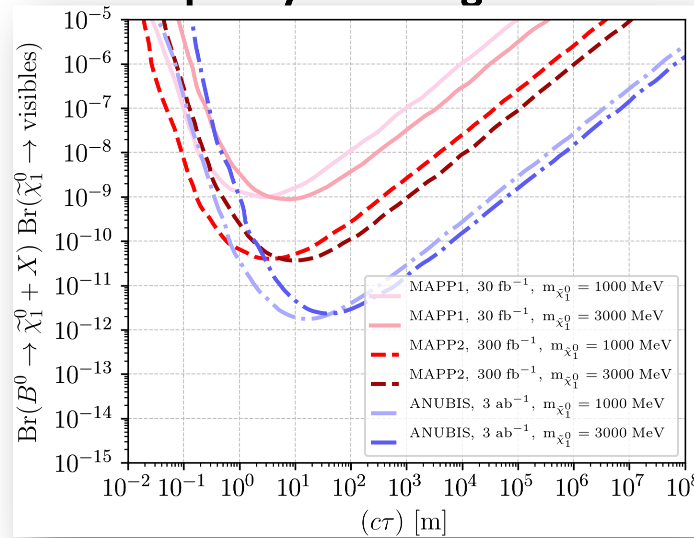
Dark Higgs scenario



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

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

R-parity violating SUSY



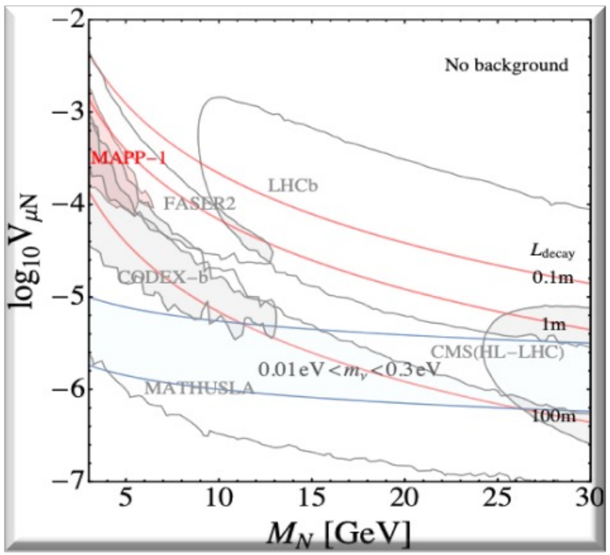
Dreiner, Günther, Wang, Phys.Rev.D 103 (2021) 075013

λ'_P for production	λ'_{131}
λ'_D for decay	λ'_{112}
Produced meson(s)	$B^0, \bar{B}^0$
Visible final state(s)	$K^\pm + e^\mp,\ K^{*\pm} + e^\mp$
Invisible final state(s) via λ'_P	None
Invisible final state(s) via λ'_D	$(K_L^0, K_S^0, K^*) + (\nu_e, \bar{\nu}_e)$

RPV couplings

MAPP-LLP – extended neutrino models

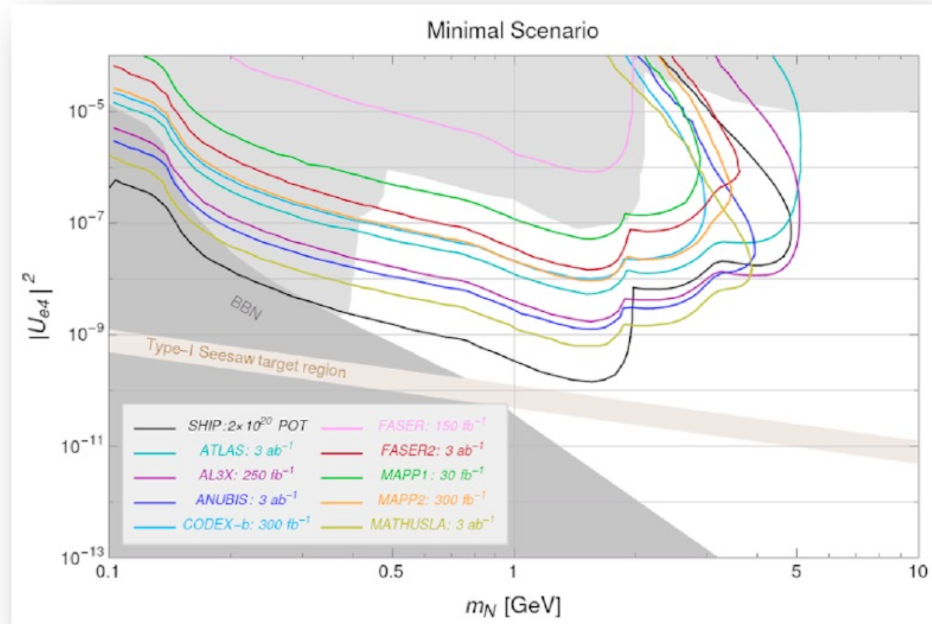
Heavy neutrino via Z' production



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})

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

Sterile neutrinos

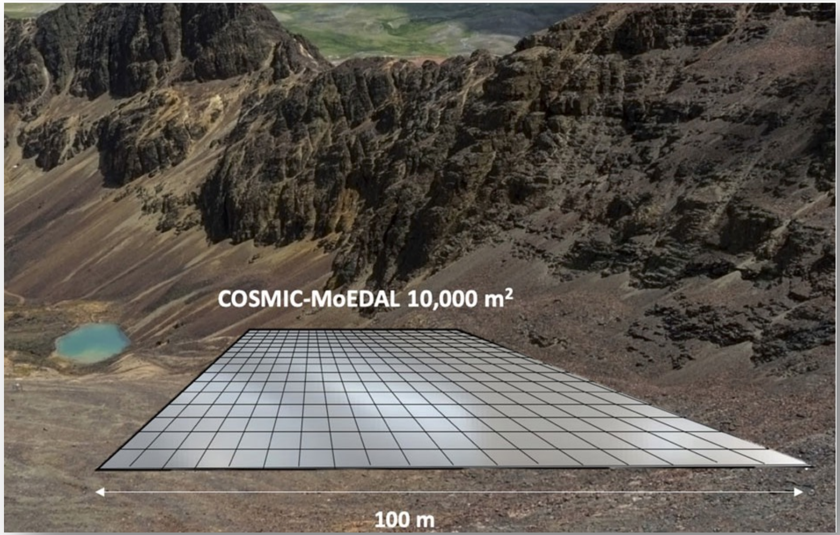


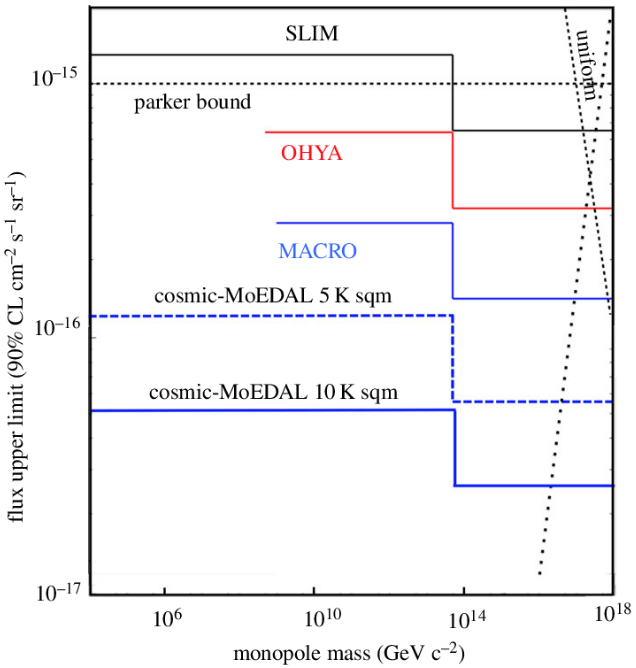
Minimal scenario: interactions are purely mediated by W- and Z-bosons via active-sterile neutrino mixing

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

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

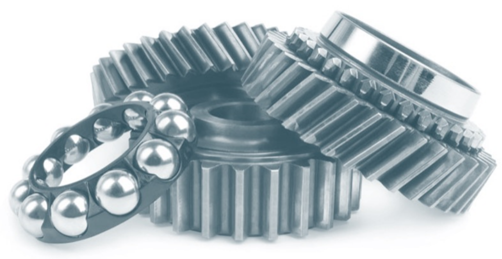
J. L. Pinfold, arXiv:1412.8677 & Phil.Trans.Roy.Soc.Lond.A 377 (2019) 2161, 20190382

Summary & outlook

- MoEDAL has published exciting results
  - sole contender in **high magnetic charges**
  - sole **dyon** search in accelerator experiment
  - first search for monopoles produced via **Schwinger mechanism**
- **MAPP** can further explore the *low ionisation* regime
  - mQP will probe ***millicharged*** particles
  - MAPP-2 with its LLP subdetector will search for neutral long-lived particles giving rise to displaced vertices ➜ dark sectors, ν portals, SUSY, ...
- Program planning for Run 3:
  - redeploy MoEDAL baseline detector
  - install MAPP detector
- **Stay tuned for upcoming results !**
  - Highly Electrically Charged Objects (HECOs) ➜ first NTD analysis!
  - CMS beam pipe scanned for trapped monopoles

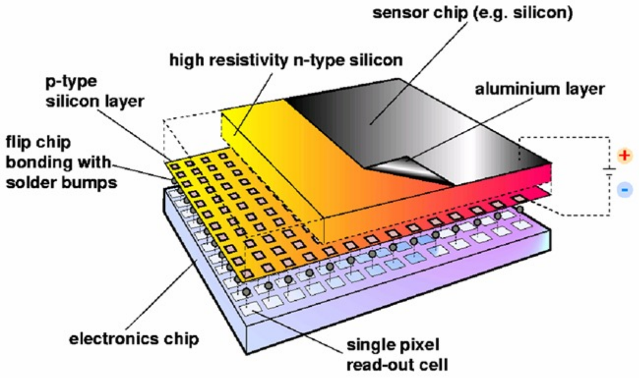
Thank you for your attention!

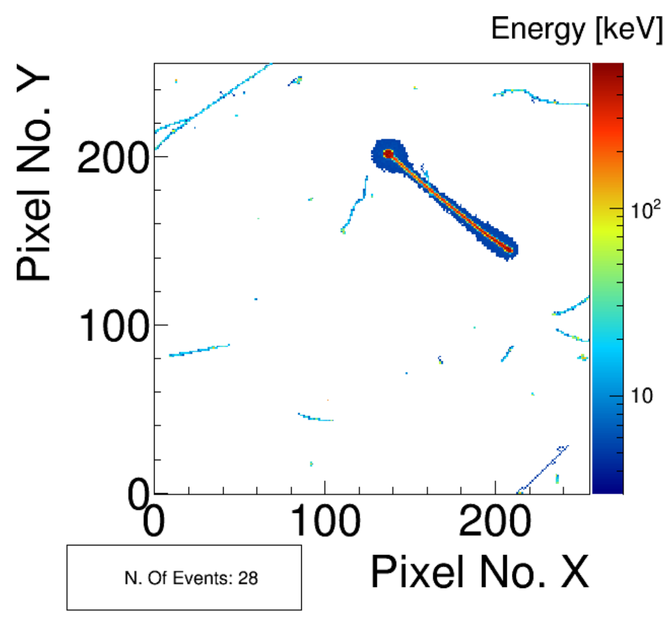
Spares



3 TimePix radiation monitor

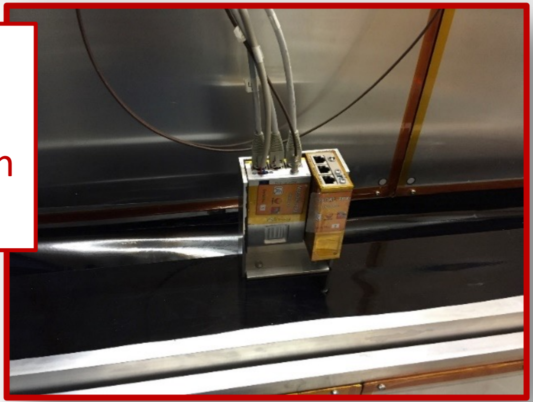
- Timepix (MediPix) chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic "bubble-chambers"
- The only active element in MoEDAL



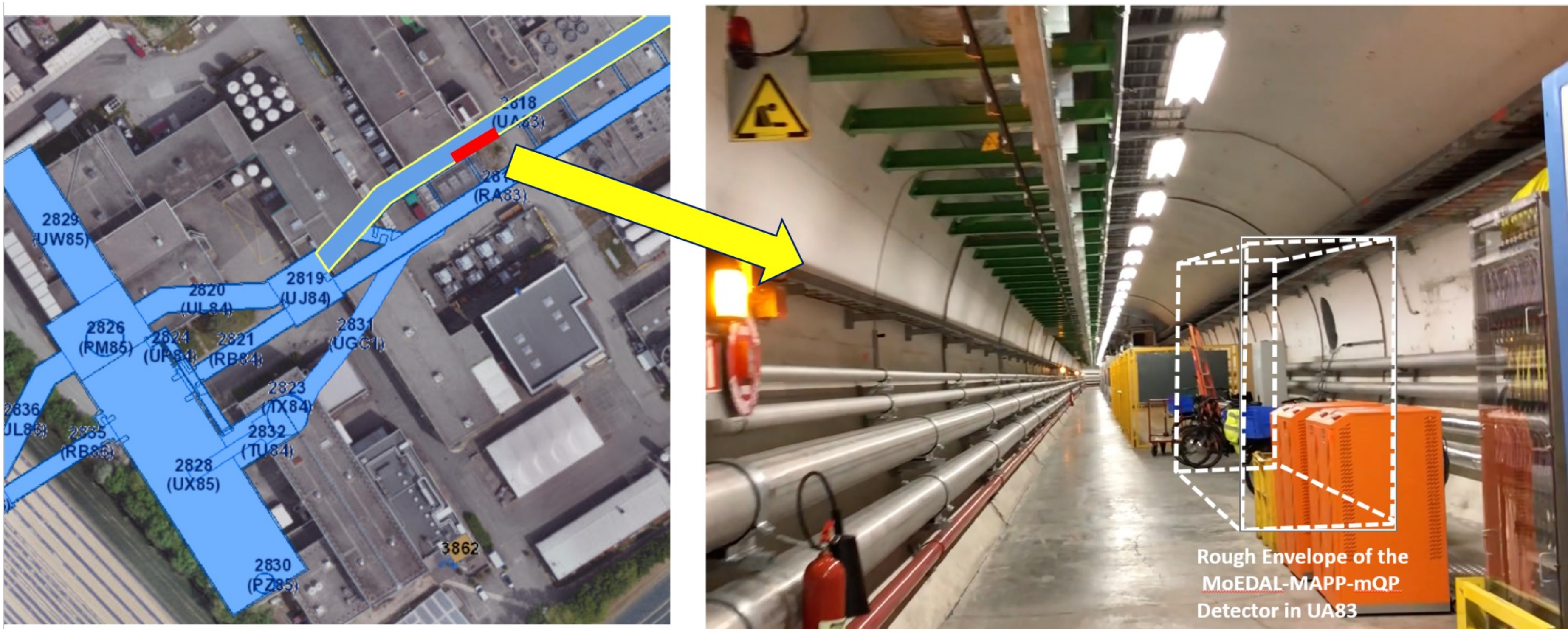


Sample calibrated frame in MoEDAL TPX04

2015 deployment of MediPix chips in MoEDAL



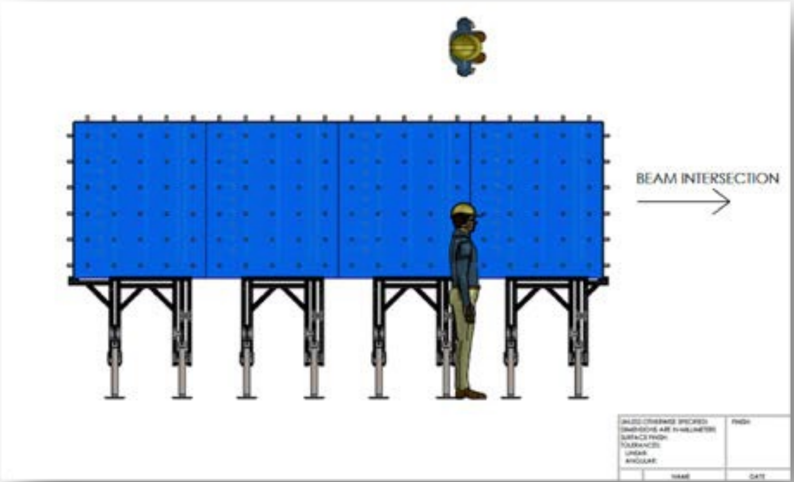
- 256×256 pixel solid state detector
- 14×14 mm active area
- amplifier + comparator + counter + timer

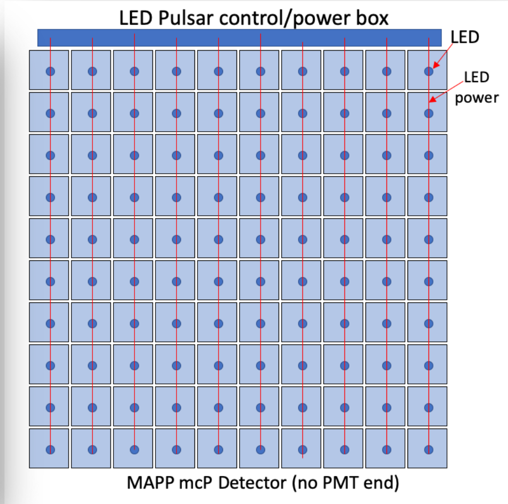

2829
(UW85)
2820
(UL84)
2819
(UJ84)
2826
(RM85)
2821
(RB84)
2831
(UGC1)
2823
(TX84)
2832
(TU84)
2828
(UX85)
2830
3862
Rough Envelope of the
MoEDAL-MAPP-mQP
Detector in UA83

The MAPP-mQP 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

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





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