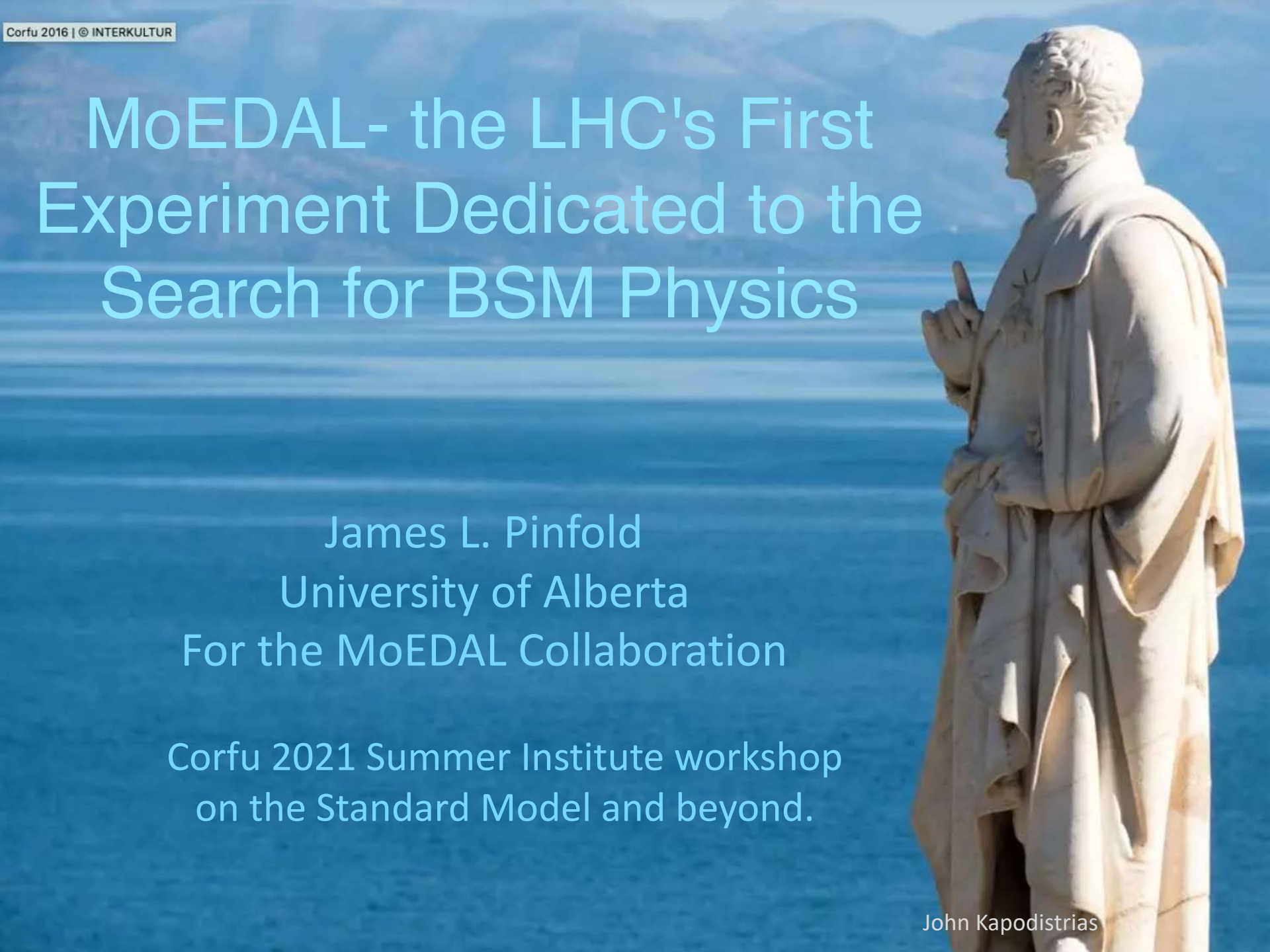


MoEDAL- the LHC's First Experiment Dedicated to the Search for BSM Physics

James L. Pinfold
University of Alberta
For the MoEDAL Collaboration

Corfu 2021 Summer Institute workshop
on the Standard Model and beyond.

MENU

a) Introduction

b) The MoEDAL detector and results from Run-2

c) The MoEDAL-MAPP project for Run-3

- The MoEDAL- MAPP installation in UA83
- Some physics studies

d) MAPP-2 upgrade for HL-LHC -- back to UGC1?

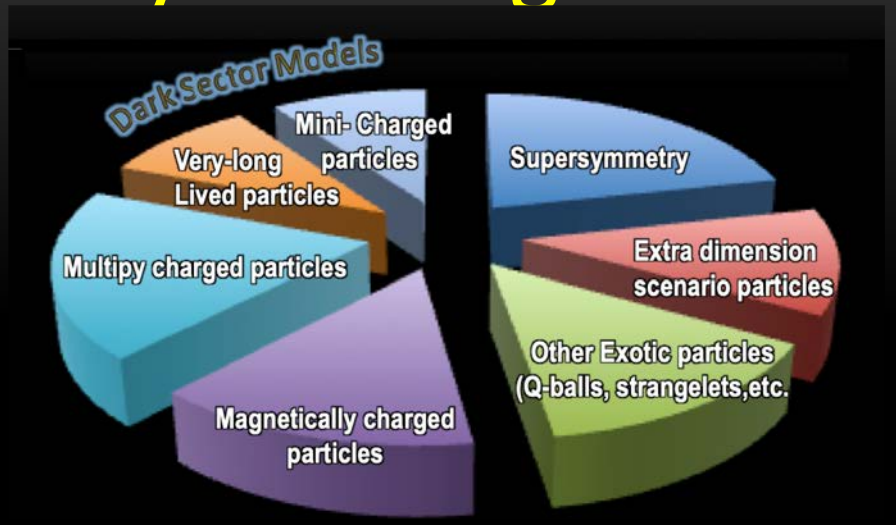
- Some physics studies

e) Concuding remarks

The LHC – no new physics yet

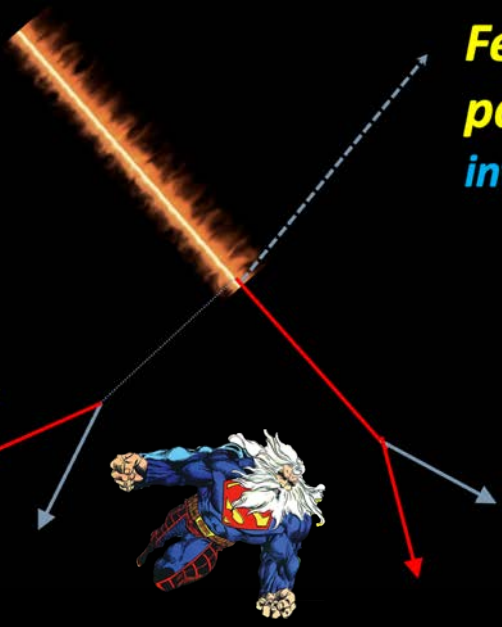
MoEDAL-MAPP – Physics Program

- *MoEDAL-MAPP will be sensitive to 3 clear avatars of new physics: HIPs, mQPs and LLPs in a way that is complementary to the general purpose LHC detectors ATLAS & CMS*



IJMPA, September 2014, Vol. 29, No. 23

Very Highly ionizing particles ***(≥ 5 times that of a standard relativistic charged particle)***



Feebly Interacting particles ***(with tiny SM interactions)***

Long lived neutral particles – ***(cτ up to ~1km)***

Very long-lived charged particles ***(with lifetimes up to ~10 years)***

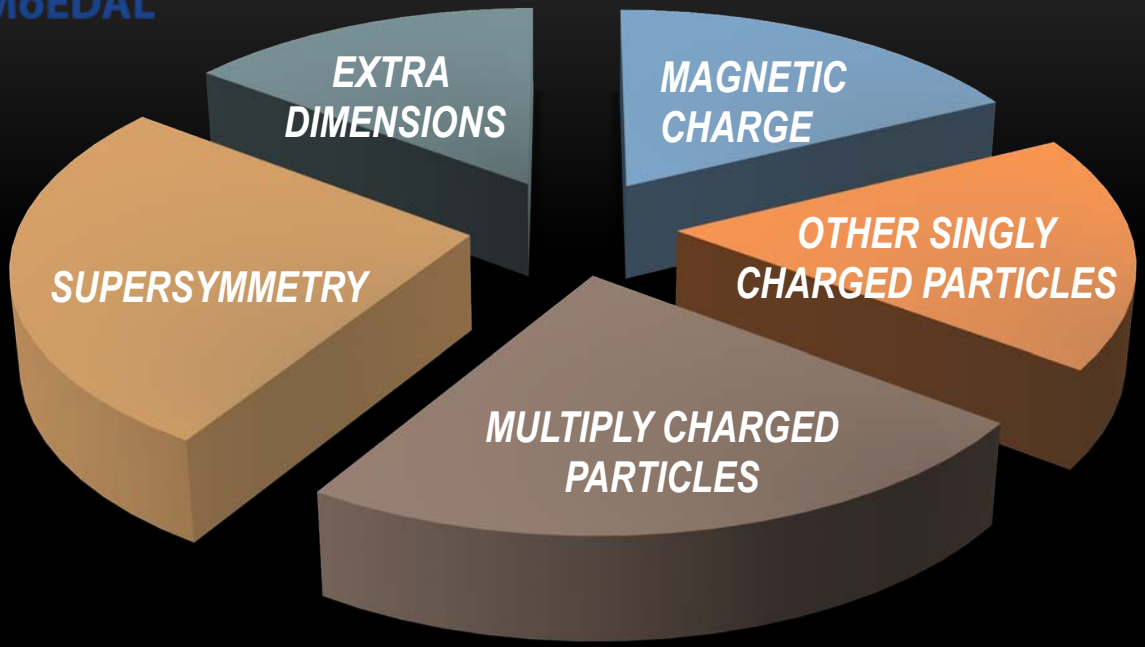
MoEDAL

The MoEDAL Detector & Results from Run-2

The Search Highly ionizing particles (HIPs)

The Search for Long-lived (neutral) Particles (LLPs)

HIP Physics at the LHC



Highly ionizing particles (HIPs)

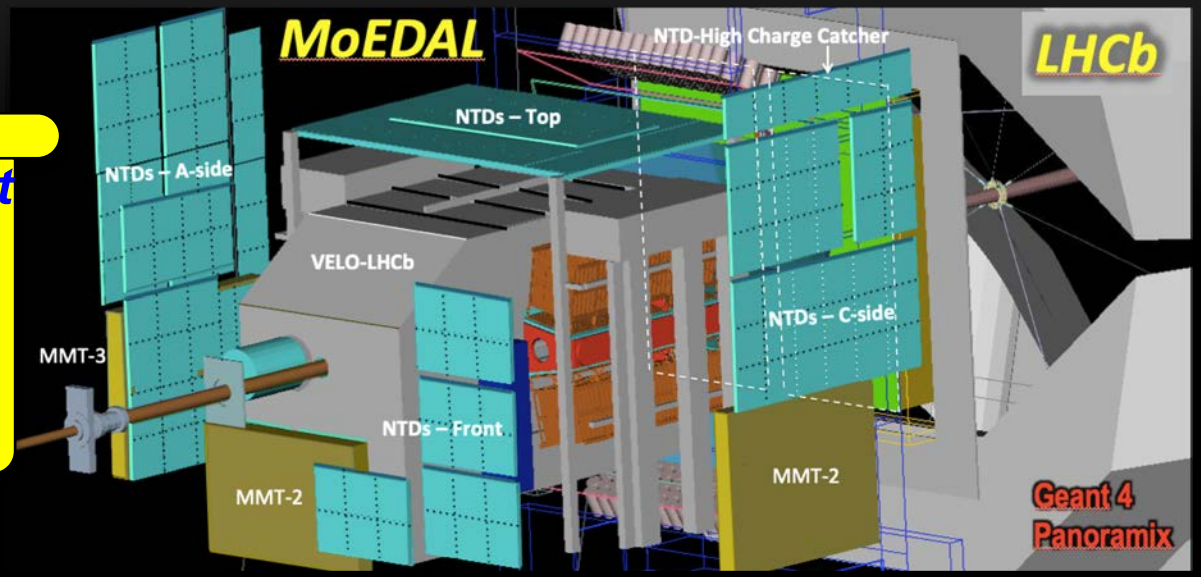
HIP physics accessible at the LHC summarized in: IJMPA, 2014, Vol. 29, No. 23

- *MAGNETIC CHARGE*
  - *Dyons/Monopoles*
  - *Electroweak Monopoles*
  - *Electroweak strings*
  - *Light t'Hooft-Polyakov monopoles*
  - *D-particles*
- *ELECTRICAL CHARGE*
  - *Q-balls & Strangelets*
  - *SUSY – eg massive sleptons, etc*
  - *Stable microscopic black holes & remnants*
  - *Doubly charged Higgs (LR Sym. Models)*
  - *Multiply charged exotic states, etc*

The MoEDAL Detector at Run-2 and Run-3

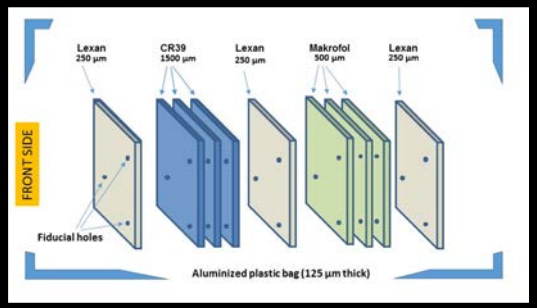
*Started data taking in 2015– **the LHC's first dedicated search experiment***

Permanent Physical record of new physics

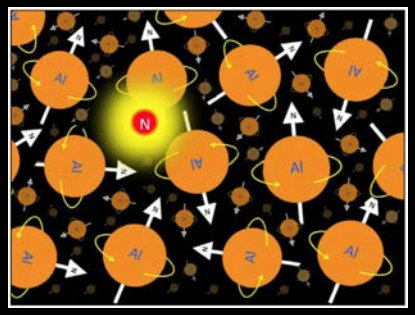


No Standard Model Physics Backgrnds

MoEDAL is made up of 3 detector system designed to search for HIPs.



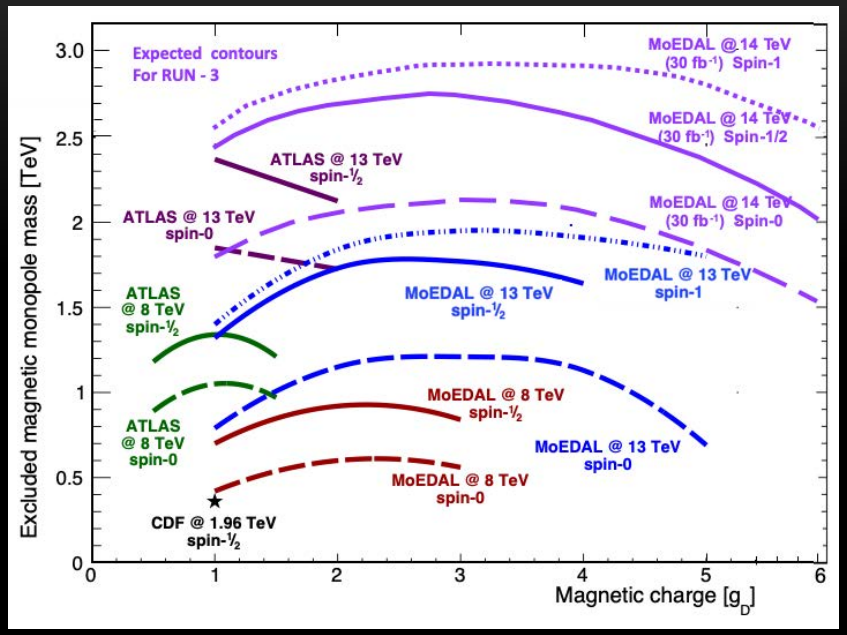
***NUCLEAR TRACK DETECTOR** Plastic array (185 stacks, 12 m^2) – Like a big Camera*

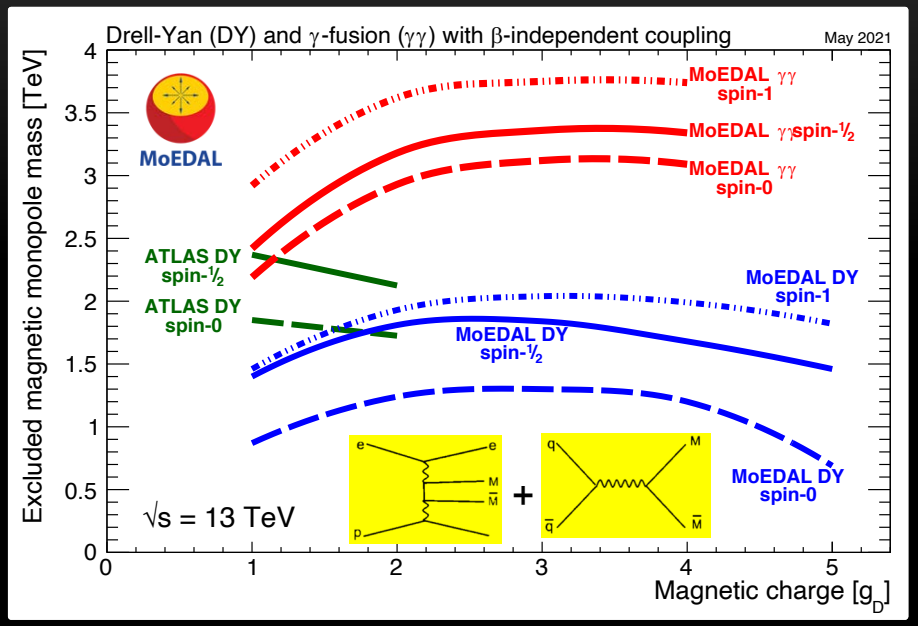


***TRAPPING DETECTOR ARRAY** A tonne of Al to trap Highly Ionizing Particles for analysis*

***TIMEPIX Array** a digital Camera for real time radiation monitoring*

Mass Limits on Multiply Charged Monopoles



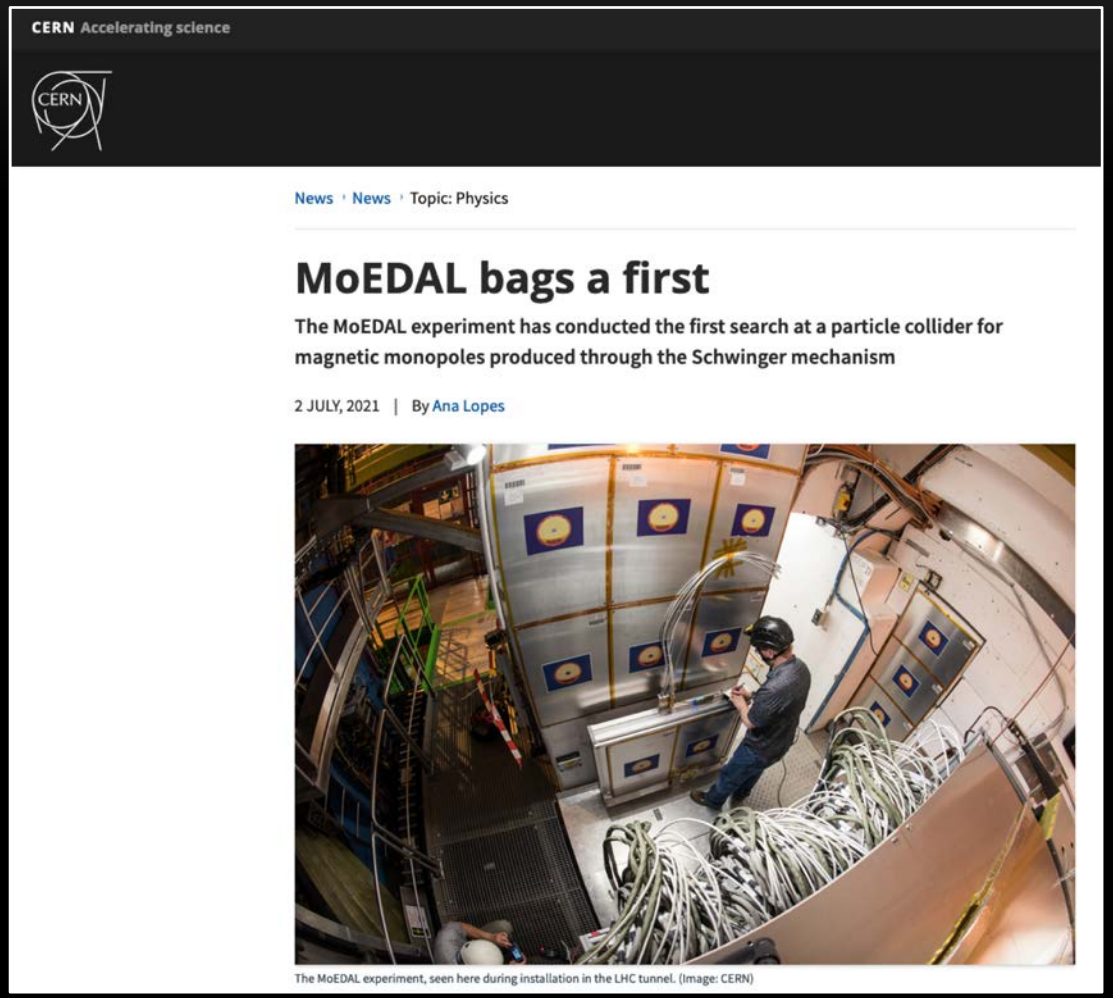


JHEP 1608 (2016) 067 PRL 118 (2017) 061801 Phys.Lett. B782 (2018) 510 PRL 123 (2019) 021802

- *So far MoEDAL has placed the world's best published direct limits on:*
  - *Multiply charged magnetic monopoles*
  - *Spin-1 monopoles*
  - *DY + Photon fusion production of monopoles*
  - *Dyons – electrically and magnetically charged particles.*

The Search for the Dyon

- *MoEDAL just completed the first direct search for Schwinger's Dyon – a particle with electric and magnetic charge*
- *We exclude dyons with:*
  - *A magnetic charge ranging up to $5g_D$ and an electric charge up to 200e with mass limits in the range 750–1910 GeV*
  - *And also monopoles with magnetic charge up to and including $5g_D$ with mass limits in the range 850 –2040 GeV.*



CERN Accelerating science

News › News › Topic: Physics

MoEDAL bags a first

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

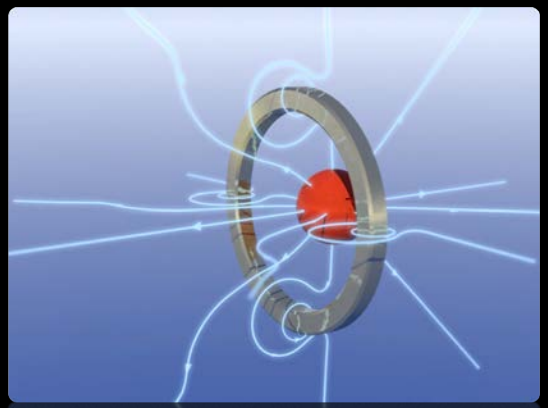
2 JULY, 2021 | By Ana Lopes

The MoEDAL experiment, seen here during installation in the LHC tunnel. (Image: CERN)

Phys. Rev. Lett. 126 (2021) 7, 071801

MoEDAL's Search for Monopoles Trapped in CMS Beampipe

- MoEDAL searched for highly charge magnetic monopoles trapped in the Run1 CMS beampipe
- We used the MoEDAL's SQUID detector based at ETH Zurich



- No evidence was seen for trapped magnetic charge
- Publication in preparation

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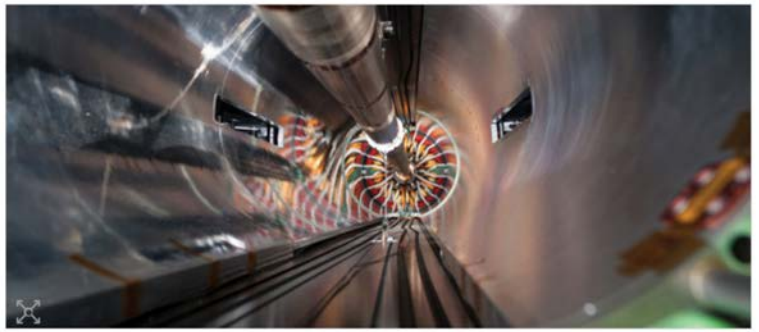
CMS beam pipe to be mined for monopoles

8 March 2019

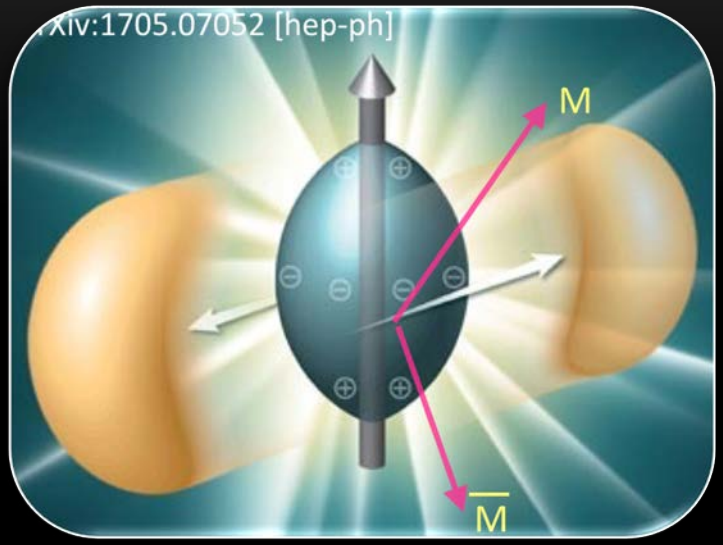


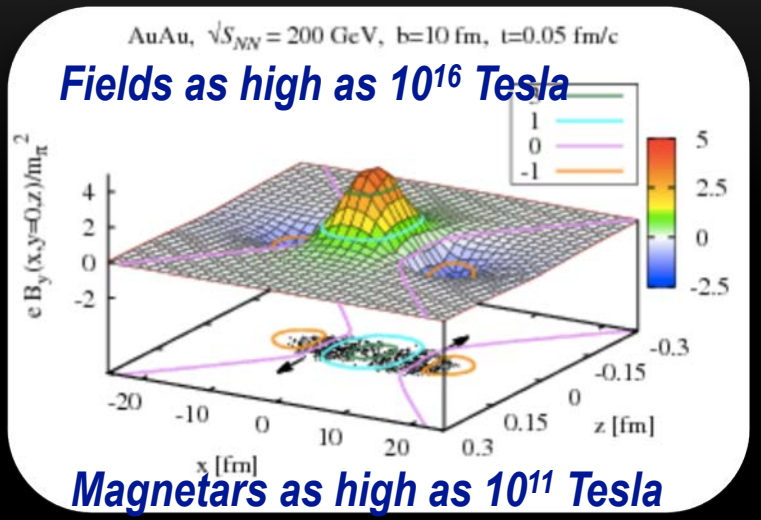
Pipe dreams: The original CMS beampipe, in use during LHC Run 1. (Credit: CERN-PHOTO-201611-288-4)

On 18 February the CMS and MoEDAL collaborations at CERN signed an agreement that will see a 6 m-long section of the CMS beam pipe cut into pieces and fed into a SQUID in the name of fundamental research. The 4 cm diameter beryllium tube – which was in place (right) from 2008 until its replacement by a new beampipe for LHC Run 2 in 2013 – is now under the proud ownership of MoEDAL spokesperson Jim Pinfold and colleagues, who will use it to search for the existence of magnetic monopoles.

Monopoles From Heavy-ion Collisions

via the Schwinger Mechanism (paper submitted)





- *Schwinger mechanism originally described spontaneous creation of $e^{--} - e^{+}$ pairs in presence of an extremely strong electric field.*
- *Probability of producing a monopole pair $\sigma_{MM} = \sigma_{Inl} V_{ST} \Gamma_T$ (where V_{st} is the space-time volume of the field, Γ_T is the rate/unit volume & σ_{inl} is the inelastic nuclear cross-section)*
- *Important benefits:*
  - *No exponential suppression for finite sized monopoles*
  - *X-sec calculation does not suffer from non-perturbative couplings as in DY*

MoEDAL @ Run-3 –Seeking SUSY

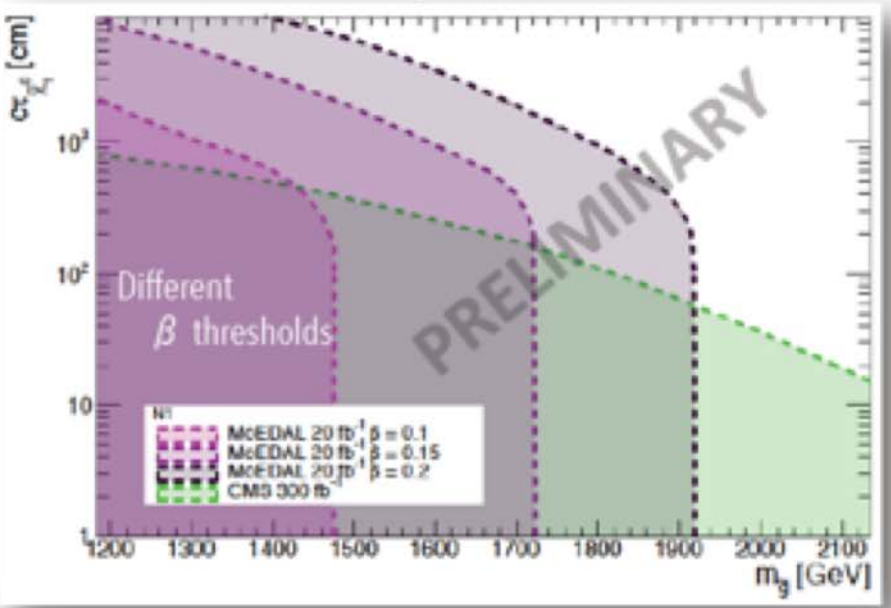
Results for $\tilde{g}\tilde{g}$, $\tilde{g} \to jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \tau^{\pm}\tilde{\tau}_1$

$\tilde{\chi}_1^0$ long-lived despite large mass split between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ ➜ decays in tracker

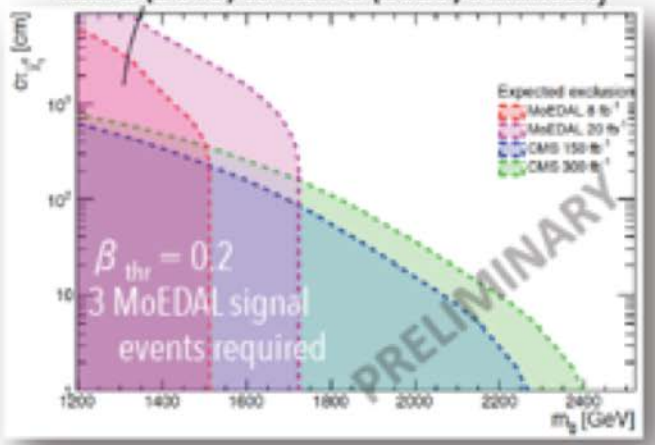
(massive) $\tau^{\pm}$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks ⇒ large impact parameter d_{xy}, d_z

$\tilde{\tau}_1$ metastable, e.g. gravitino LSP ➜ detected by MoEDAL

End-of-run-3 (2023) luminosity



Run 2 (2018) vs. Run-3 (2023) luminosity



- CMS suffers twice:
  a) no pixel hit
  b) too large impact parameters
- MoEDAL can cover long-lifetime region inaccessible by ATLAS/CMS even with a *moderate* NTD performance $z/\beta > 10$

Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event

MoEDAL Searches for Massive Electrically Charged Particles

- *MoEDAL is now expanding its reach in the arena of massive slow moving and long-lived electrically charged particles*

MoEDAL

The MoEDAL –MAPP-mQP Project for Run-3

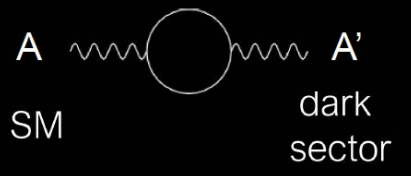
The Search for (HIPs)

The Search for LLPs)

The Search for Feebly Interacting Particles (FIPs)

Searching for Charged FIPs at the LHC

- *The SM can be extended by consistently introducing fields eg just adding a mini-charged field to the SM Lagrangian.*
- *Another Standard motivation:- Introduce a new, hidden U(1) with a massless field A', a "dark photon" that couples to a massive "dark fermion" ψ'*



$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}'(\gamma^\mu\partial_\mu + ie'\gamma^\mu A'_\mu + iM_{\text{mCP}})\psi' - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

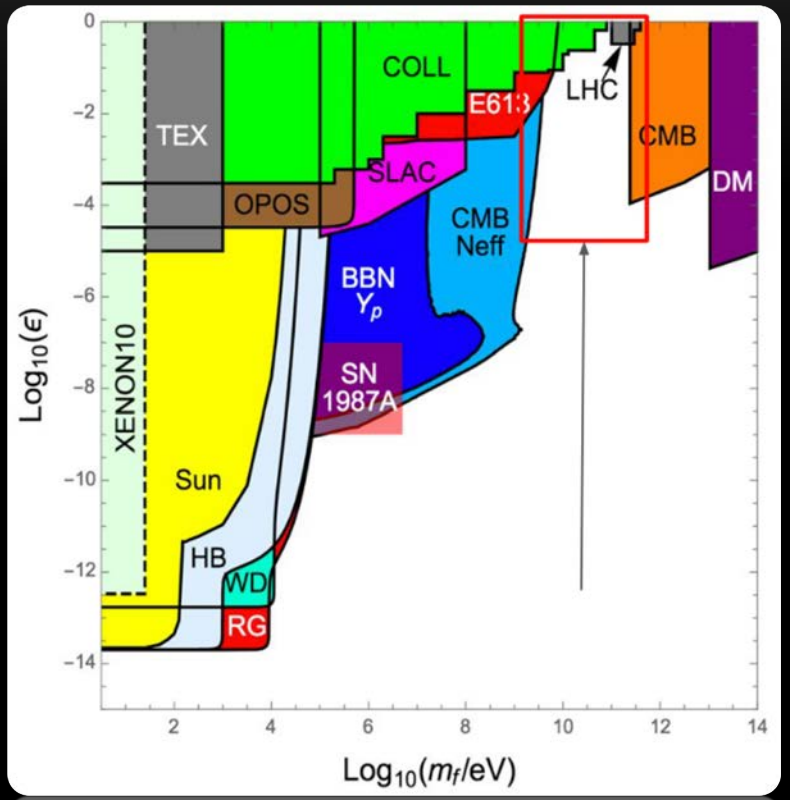
massless "dark photon" — "dark fermion" with mass M_{mCP}, charge e' — mixing term

$\kappa \sim 10^{-3} - 10^{-2}$ (naturally $\sim \alpha/\pi$)

- *Ψ' has a charge under the new U(1) of e' and a mass M_{mQP}*
- *A Gauge transformation of $A'_\mu \to A'_\mu + \kappa B_\mu$ introduces the coupling $\overline{\psi'}\kappa e'\gamma^\mu B_\mu\psi'$*
- *As a result a coupling emerges between a dark fermion and SM photon of charge $\kappa e' \cos\theta_W$*
- *mQP parameters are entirely defined by their mass and charge*

The mQP Phase Space

- *Direct constraints on mQPs from collider + beam dump experiments and indirect constraints from cosmological, supernova and solar bounds cover a wide range of masses/charges shown in the figure*
- *The GeV mass region marked in the figure is reachable by MAPP-mQP and milliQan.*
- *However, the general purpose LHC detectors ATLAS and CMS can only reach down to a charge of greater than ~ e/3*

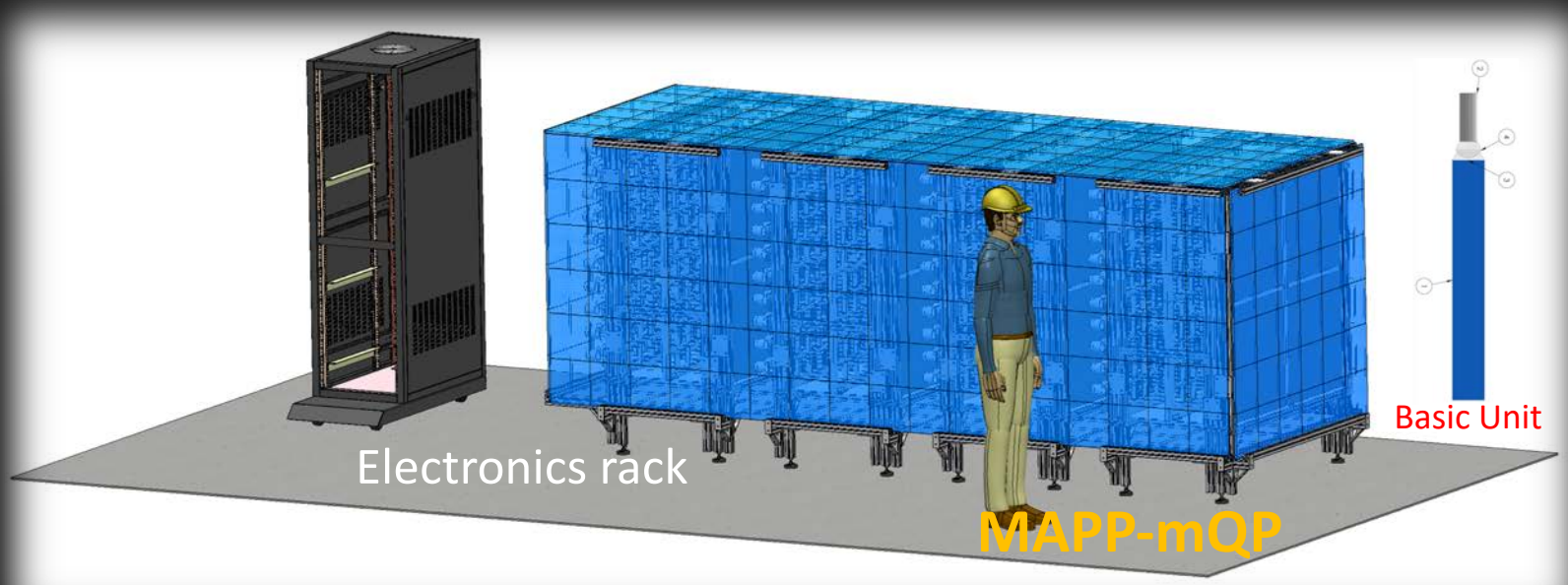


mQp particles from the Sun arXiv:1511.01122

From UGC1 to UA83 Location

CERN safety group found that UGC1 needs 6 months of engineering work to be made Useable – we moved to UA83 so that we could take data in Run-3

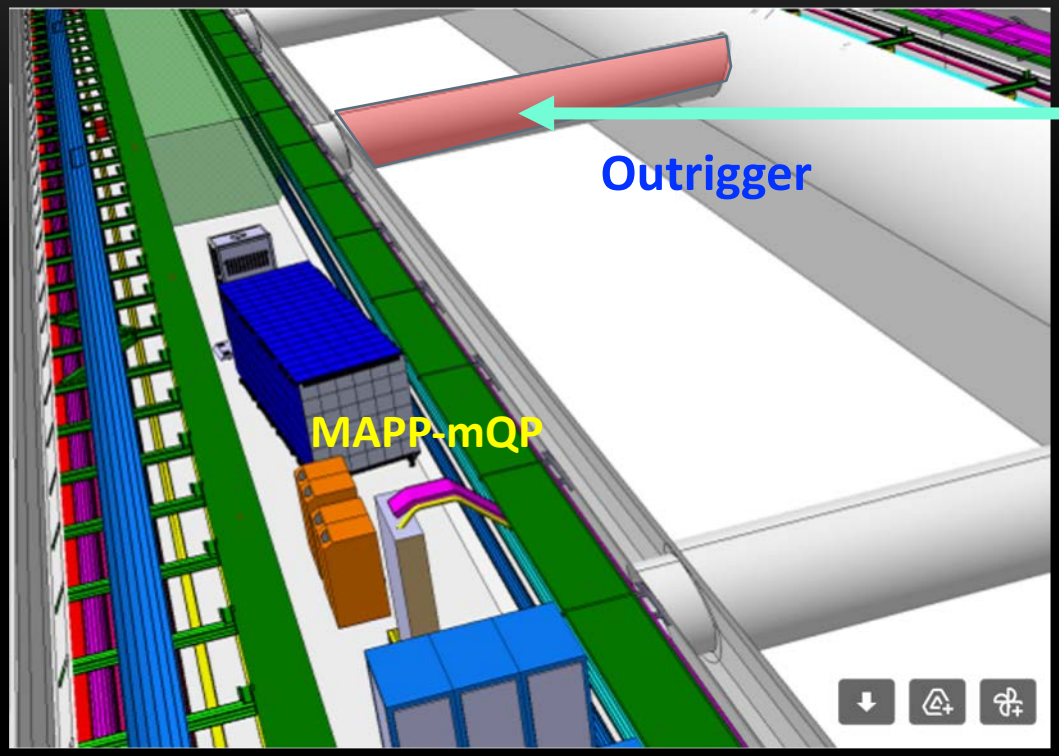
The MAPP-mQP in UA83

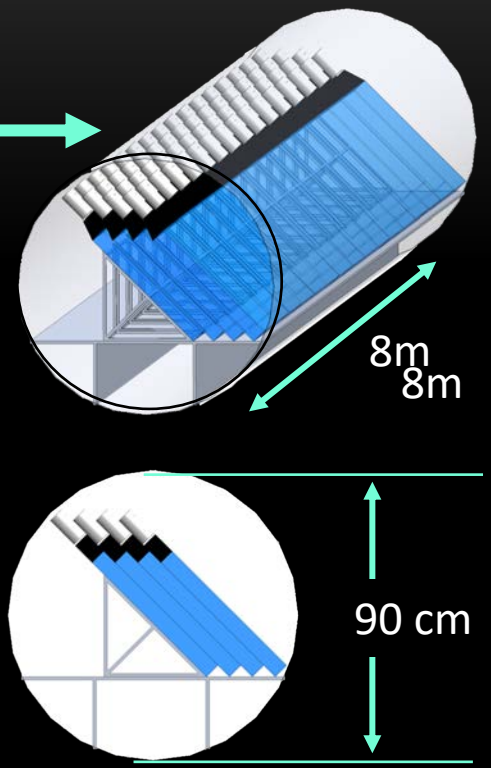


- *The MAPP-mQP detector will be deployed in UA83 for RUN-3.*
  - *It weighs 4-5 tonnes with size ~1.5 X 2.5 x 4.0m^3*
  - *It is surrounded by a veto layer to help eliminate cosmic ray backgrounds.*
  - *Consists of 400 scint. bars (10x10x75 cm^3) in 4 sections readout by 400 PMTs*
  - *Uses FPGA-based trigger, readout over the internet operating in standalone mode*
  - *Calibration using blue LEDs (in each bar) + neutral density filter absolute calibration*

The Outrigger Detector

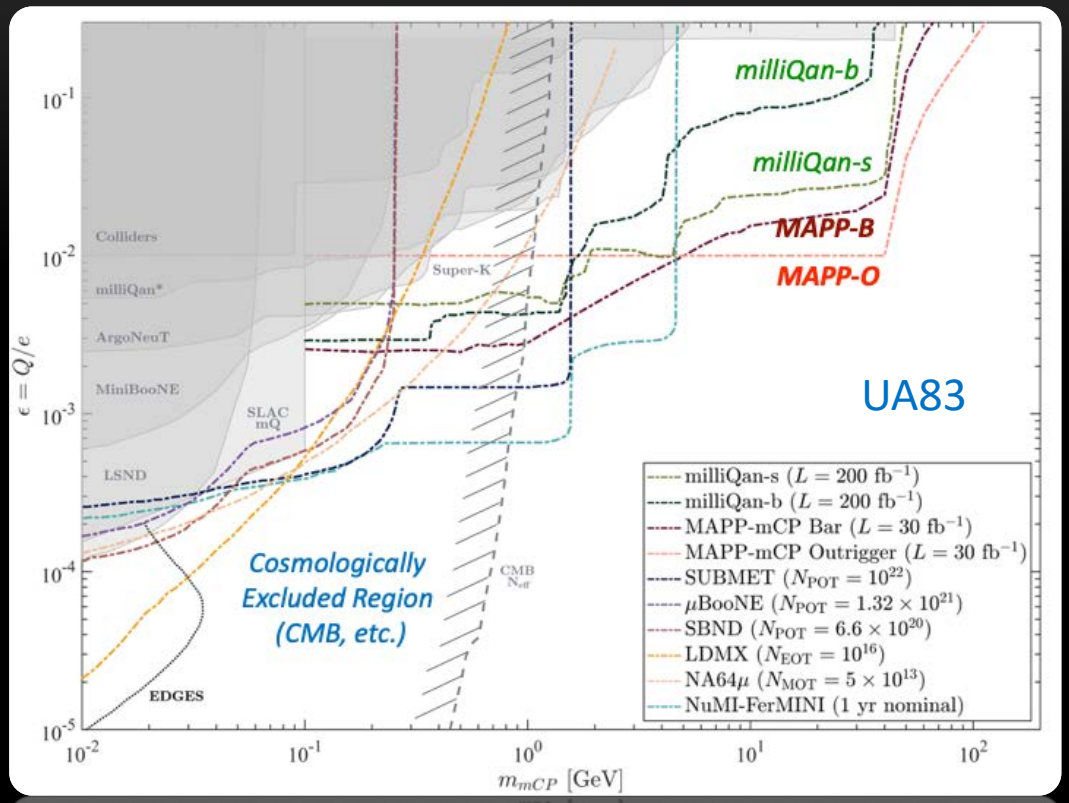
MoEDAL





- *The contribution of scintillator slabs from the EXO-200 experiment has enabled us to complete our plans for an outrigger detector for the MAPP-mQP to improve its sensitivity at high mass*
  - *The basic unit of the outrigger is a 50 cm x 50 cm x 5 cm plate readout by a PMT on a light guide. These basic units are combined in 4 layer, 8m long, 64 detector array that fill the pipe joining UA83 and the beam-line tunnel*

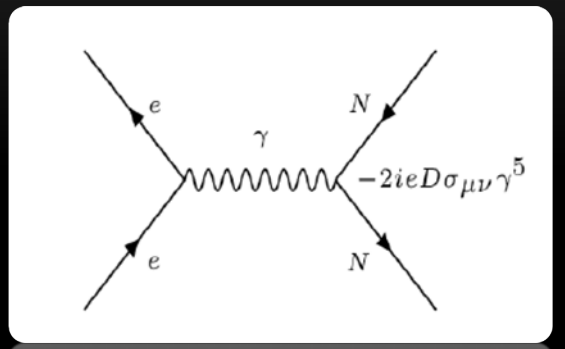
The MAPP-mQP & milliQan Sensitivity

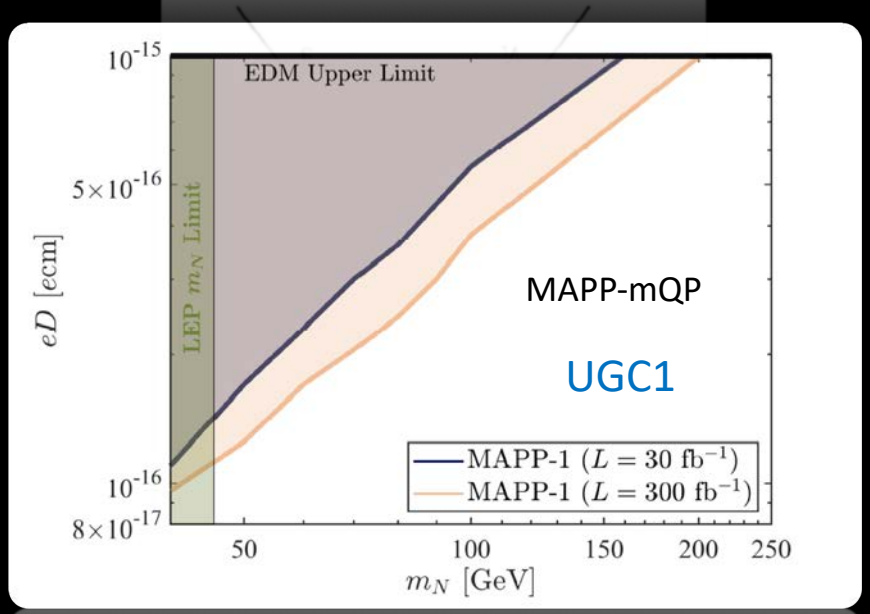


- *NB the MAPP-mQP sensitivity assumes no backgrounds and 100% efficiency and does not include the outriggers.*
  - *millQan does include backgrounds and efficiency*
- *Expect to define the world's limits for ~5 GeV < mf < ~100 GeV*

A FIP Particle Due to Large EDM*
(*Electric Dipole Moment)

- *There are many BSM models which predict large particle EDMs.*
- *EG, a heavy neutrino a member of a 4th generation lepton doublet,with EDM introduced within a dimension-five operator has been hypothesized (Phys. Lett. B* 802 (2020) 135204)
- *An EDM can cause ionization although at a very low level. but it can be detected by MAPP-mQP and milliQan if the EDM > ~ 10^{-16} e.cm*
- *Hence the heavy neutrino in this model can be considered to be a charged FIP*
- *The limits for heavy neutrino DY production at the LHC are shon opposite*





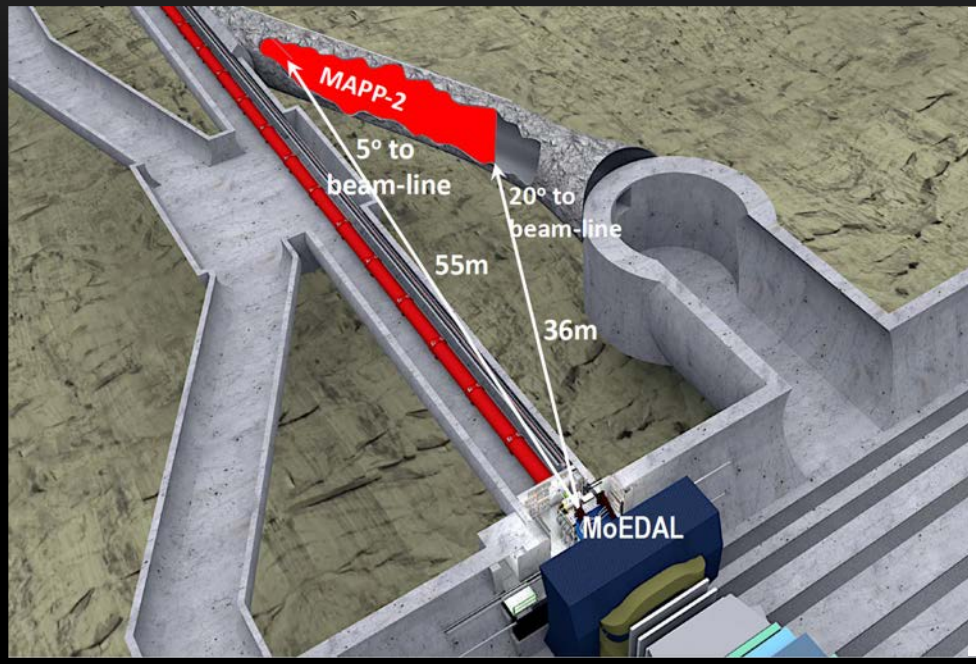
Phys. Lett. B 802 (2020) 135204
Inspired by M. Sher and J. Stevens, Phys. Lett. B777(2018)

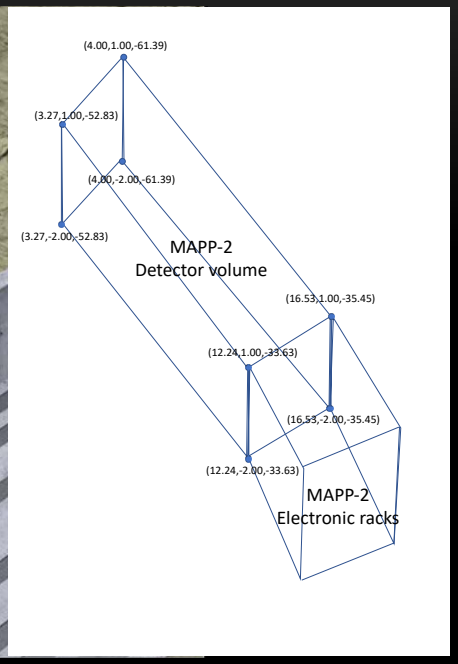
MoEDAL

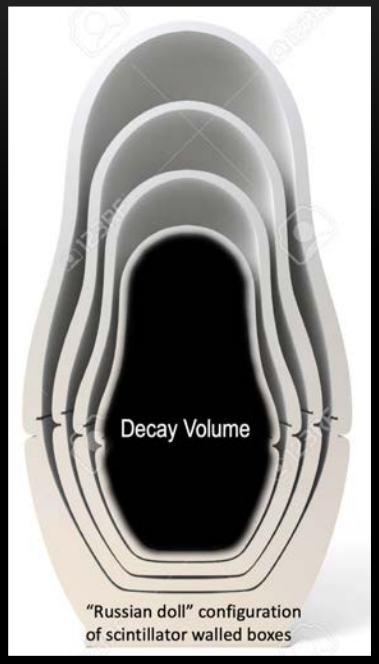
The MAPP-2 Upgrade for the HL-LHC -- back to UGC1

The Search for very long lived charged and neutral particles VLLPs

Phase-2: MAPP-2 for HL-LHC



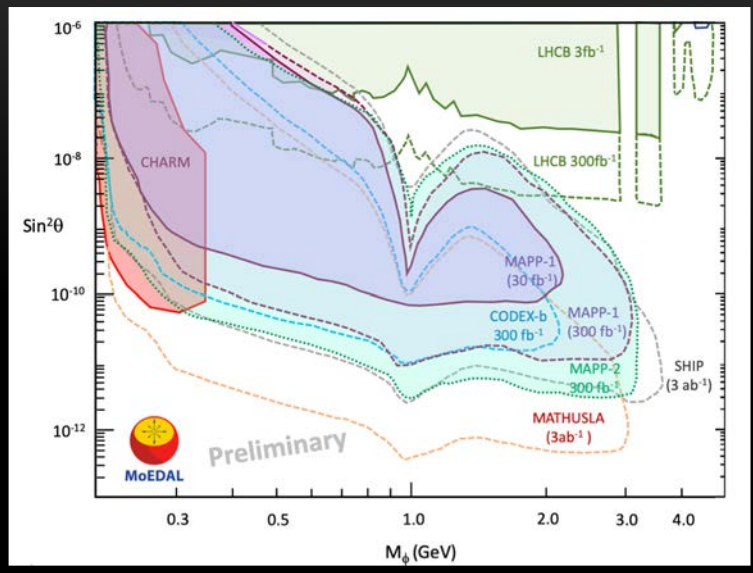




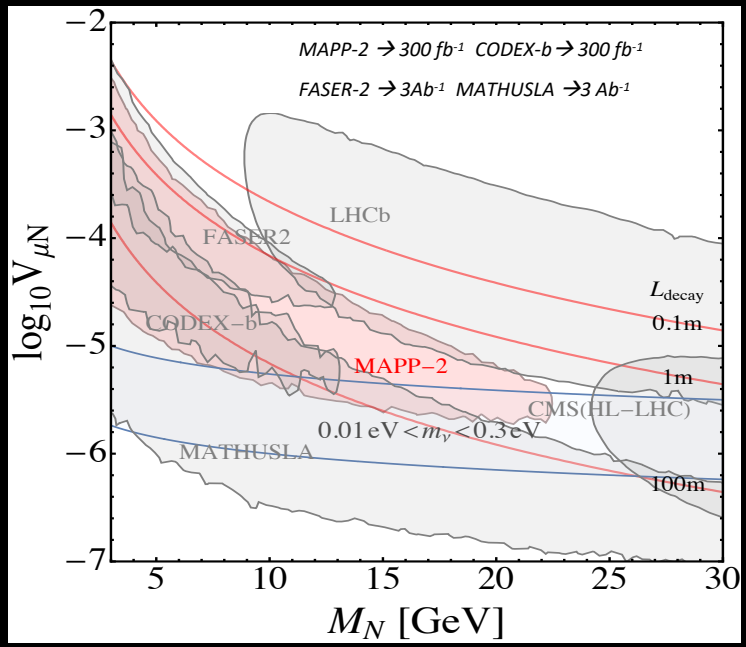
- *The UGC1 gallery would be prepared during LS3 prior to HL-LHC*
- *The MAPP-2 detector extends down the length of the UGC1 gallery*
- *The tracking detectors would form 3 or 4 hermetic containers - one within the other – lining the walls of UGC1*
  - *Detector technology large tiles with x-y WLS fibre readout with resolution $\lesssim$ 1cm/measurement*

MAPP-2 (LLP): Example Physics Studies

- *Benchmark process:*
  - *Where the Higgs mixing portal admits inclusive B → $X_s\phi$ decays, where φ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\vartheta \ll 1$.*
- *TOP: MAPP-2 each for 300 fb^{-1} compared to CODEX-b, SHIP, MATHUSLA.*
- *Bottom: Pair production of right-handed neutrinos from the decay of an additional neutral Z^0 boson in the gauged **B-L** model – Phys. Rev. D100 (2019), 035005.*
- *No backgrounds/efficiencies are included*



See Phys. Rev. D97 (1) (2018) 15023 for CODEX-b results.



Concluding Remarks

"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes." Marcel Proust

Dedicated search experiments such as MoEDAL-MAPP are the "new eyes" of the LHC