MoEDAL-MAPP
(the LHC's 1st Dedicated Search Experiment for BSM Physics)
Progress & Future Plans

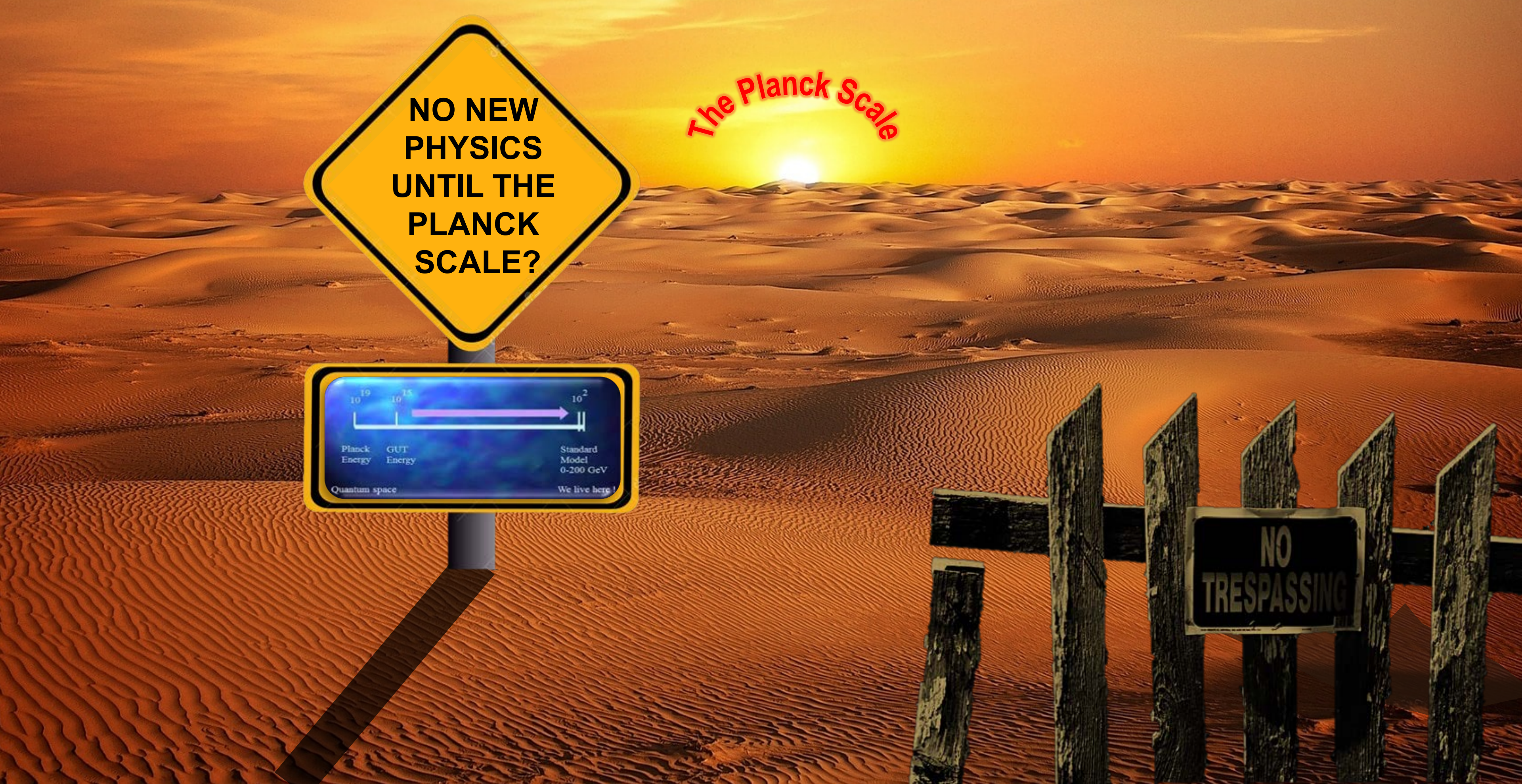
James L. Pinfold
University of Alberta
For the MoEDAL Collaboration

Corfu 2022 Summer Institute workshop
on the Standard Model and beyond.

John Kapodistrias

Where is the New Physics?

Are we seeing the edge of the Great Particle Physics Desert?



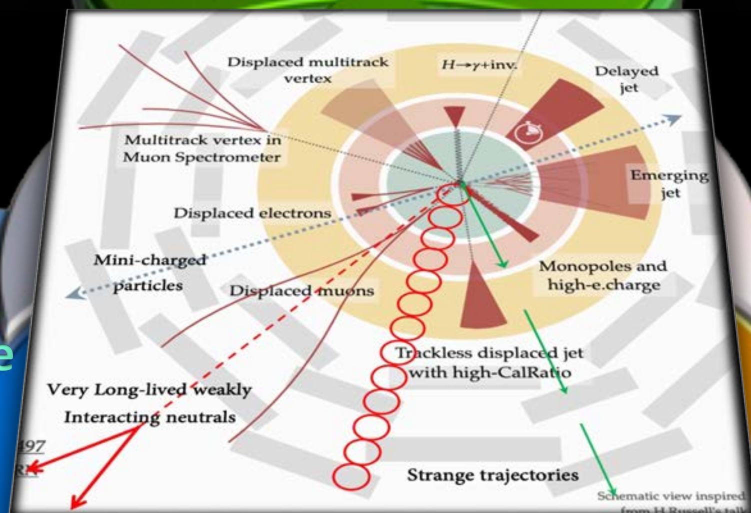
Avatars of New Physics.......

MoEDAL MAPP

$$\Delta I = \frac{4\pi N}{L} g_D = 2\Delta I_0$$

Long-lived Particles (LLPs)

$$\Gamma = \frac{1}{\tau} \sim g^2 \left(\frac{m}{M}\right)^n m$$



Magnetic charge

$-dE/dx \propto g^2$

$g = n68.5e$

Electric charge

$-dE/dx \propto z^2/\beta^2$

$Z \geq 1$ $\beta < 1$

Highly-ionizing particles (HIPs)

Electric charge

$-dE/dx \propto Z^2/\beta^2$

$Z(<<1)$ $\beta(\sim 1)$

Feebly interacting particles (FIPS)

.........for which ATLAS & CMS are not optimized

MoEDAL-MAPP Collaboration

70 physicists at 26 Institutes

UNITED KINGDOM
Imperial College London
Kings College London
Queen Mary University
Track Analysis Systems Ltd
IRIS Canterbury

KOREA
Centre for Quantum Spacetime, Seoul

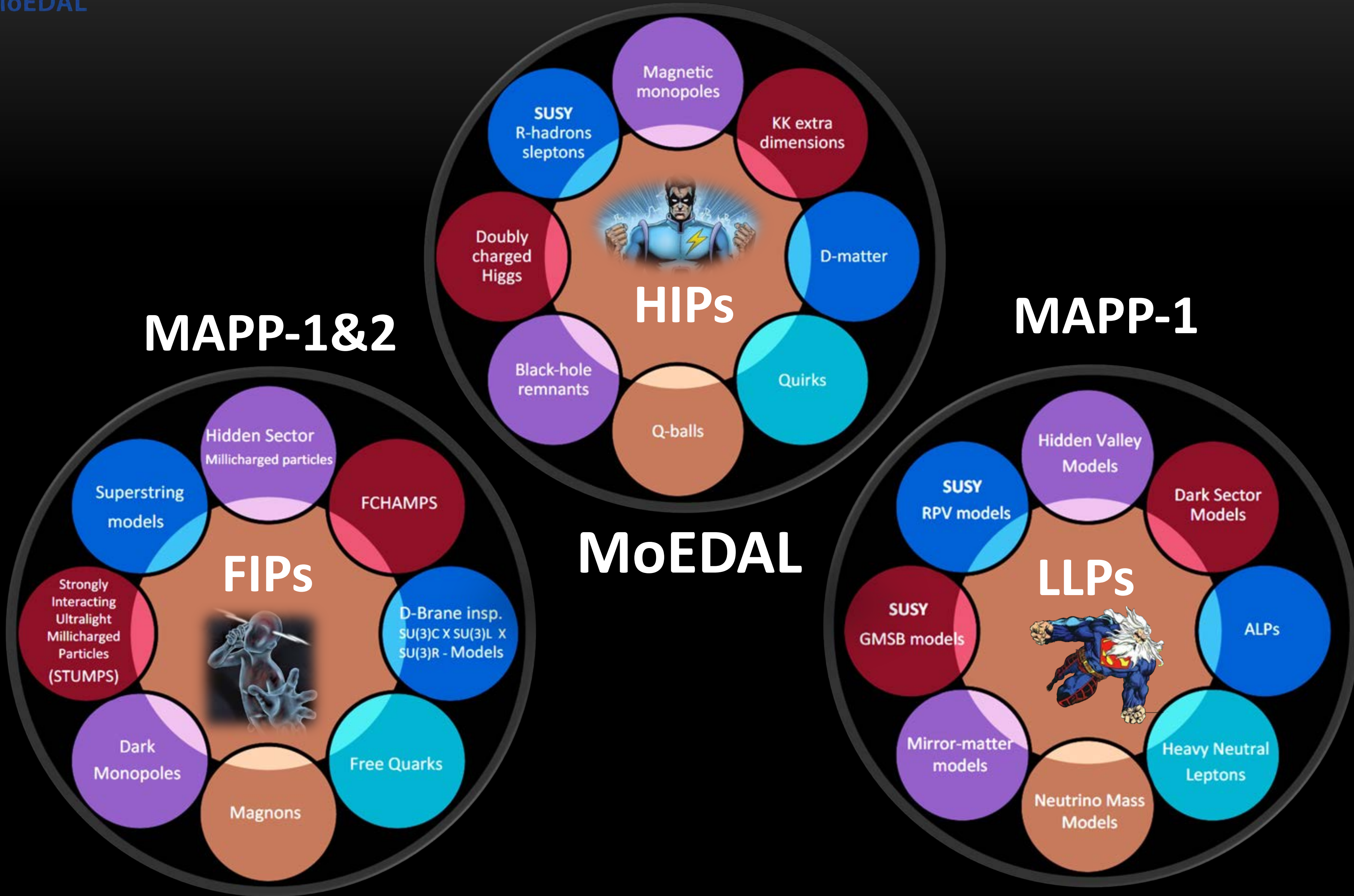
NORTH AMERICA
University of Alabama
University of Alberta
University of British Columbia
Concordia University
University of Montreal
University of Regina
Tuft's University
University of Virginia

EUROPE
Technical University of Athens
University of Bologna & INFN Bologna
CERN, Switzerland
Czech Technical University (IEAP)
University of Helsinki
Institute of Space Sciences Romania
University of Valencia (IFIC)
Vaasa Universities

INDIA
University of Calcutta
National Institute of Technology, Kuruksetra

The LHC's First Dedicated Search Experiment (approved by the CRB in 2010)

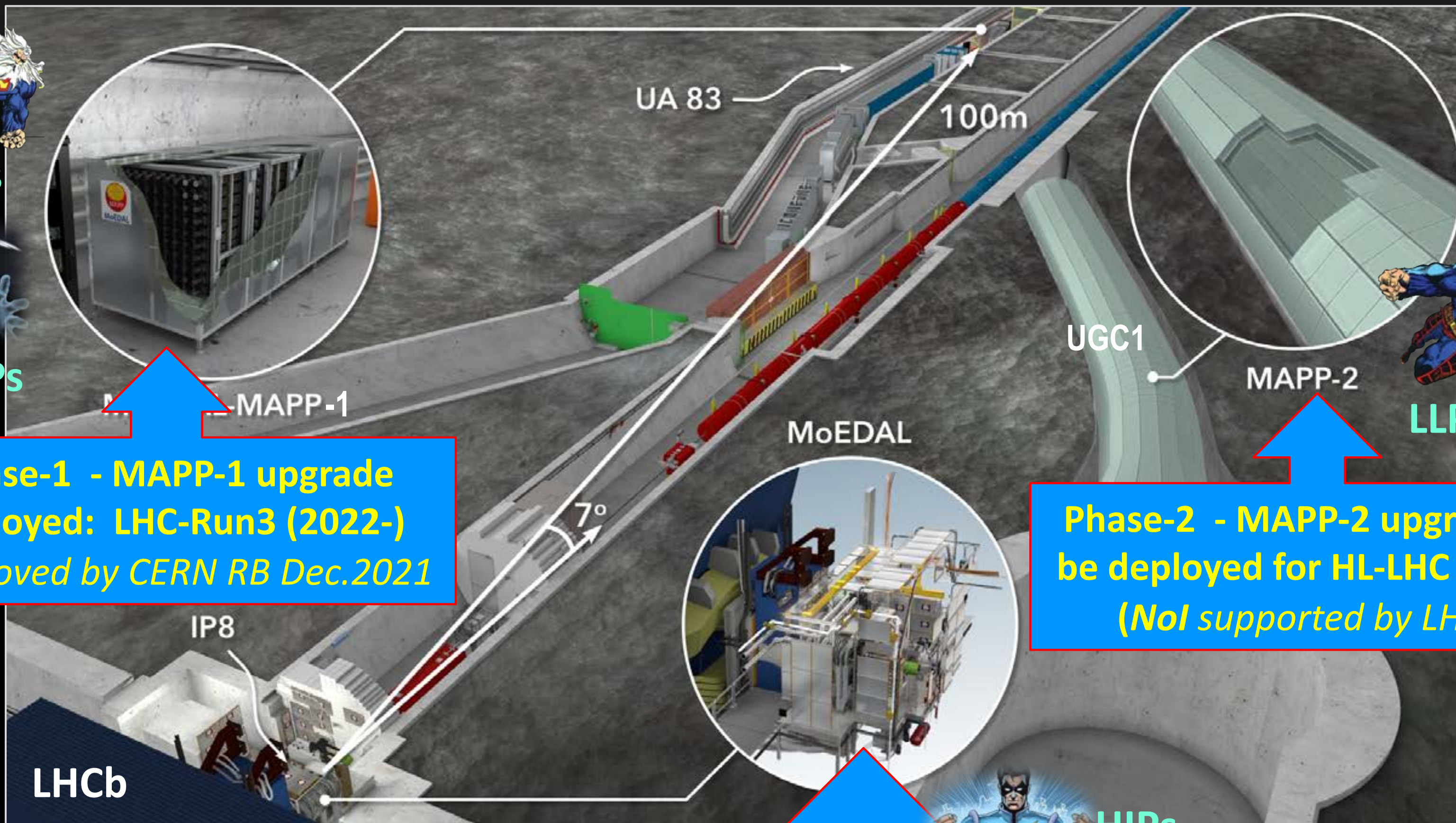
MoEDAL-MAPP Physics Program



MoEDAL-MAPP a > 25 Year Project

LLPs

FIPs



LLPs

HIPs

Phase-1 - MAPP-1 upgrade deployed: LHC-Run3 (2022-)
(*Approved by CERN RB Dec.2021*

Phase-2 - MAPP-2 upgrade to be deployed for HL-LHC (2027-)
(*NoI supported by LHCC)*

Phase-0 - MoEDAL Detector deployed for LHC-Run-1& 2 (2010 - 18) and Phase-1 - Run-3 (2022 -)
(Approved by CERN RB in 2010 & reapproved for LHC's Run-3 in Dec. 2021

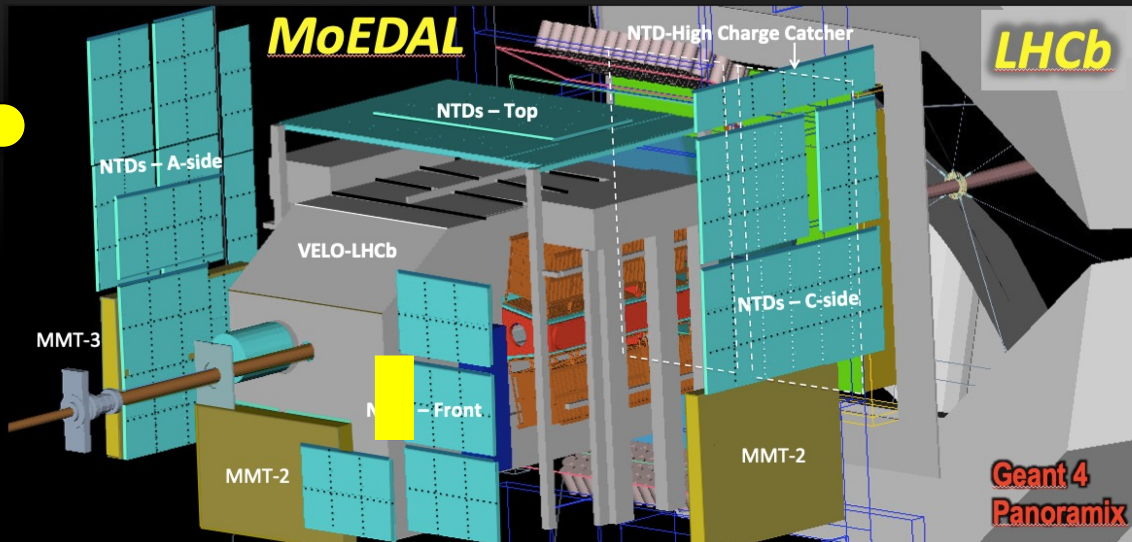
Phase 0 - the MoEDAL Detector at Run-1&2 [2011-2018]

The Search Highly ionizing particles (HIPs)

MAPP
MoEDAL

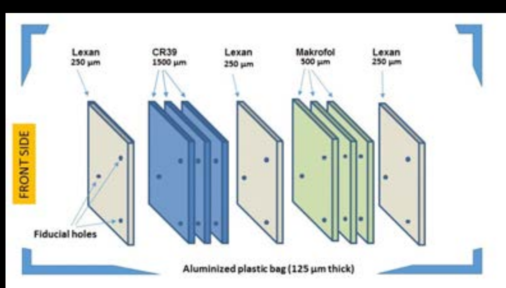
The MoEDAL Detector at Run-2

Permanent Physical record of new physics

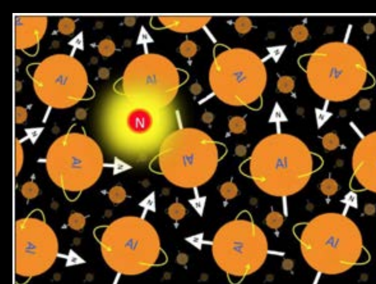


No Standard Model physics backgrounds

Passive detectors - No Trigger Requirements



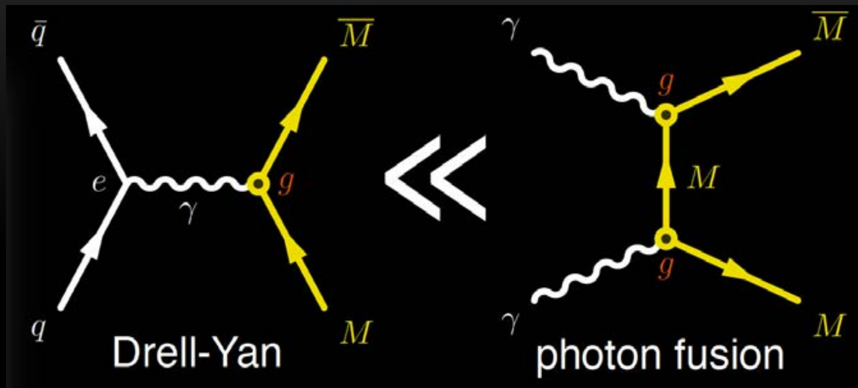
NUCLEAR TRACK DETECTOR Plastic array (186 stacks, 12 m^2) – Like a big Camera

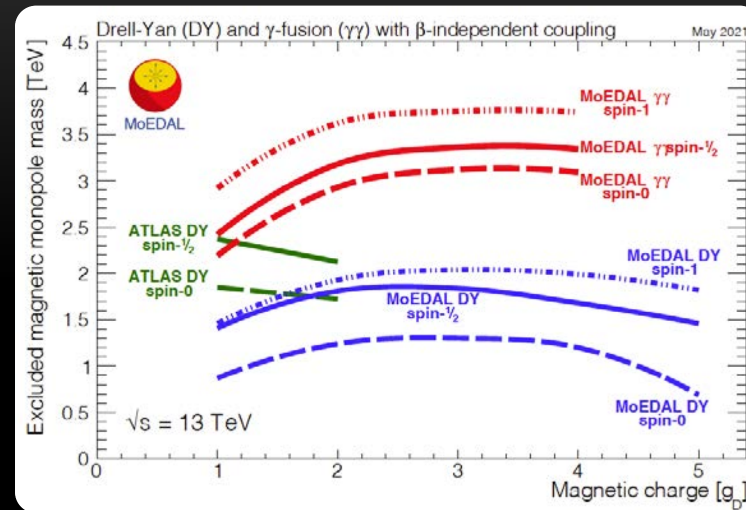


TRAPPING DETECTOR ARRAY A tonne of Al to trap Highly Ionizing Particles for analysis

TIMEPIX Array a digital Camera for real time radiation monitoring

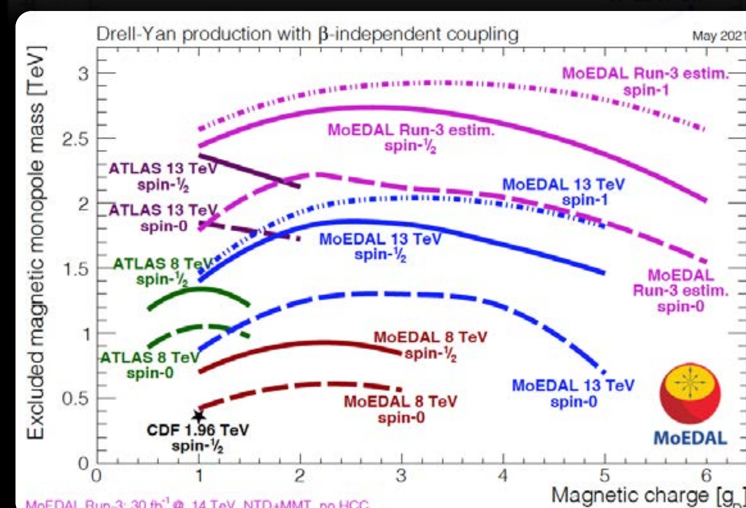
MoEDAL's Monopole Searches





JHEP 1608 (2016) 067, PRL 118 (2017) 061801, PLB 782 (2018) 510, PRL 123 (2019) 021802, PRL 126 (2021) 071801

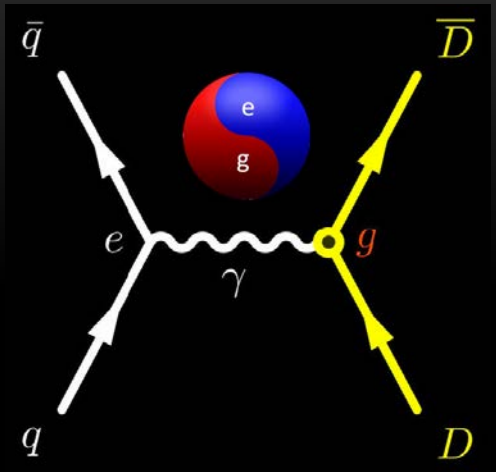
- *Unique features of MoEDAL's Search for Monopoles at the LHC*
  - *We consider β-dep./indep. couplings*
  - *Spin-1 monopoles*
  - *γγ fusion*
- *More results from Run-3 & HL-LHC*



MoEDAL has set the world's best monopole mass limits

MoEDAL, Phys.Rev.Lett. 123 (2019) 021802.
Eur.Phys.J.C 78 (2018) 966

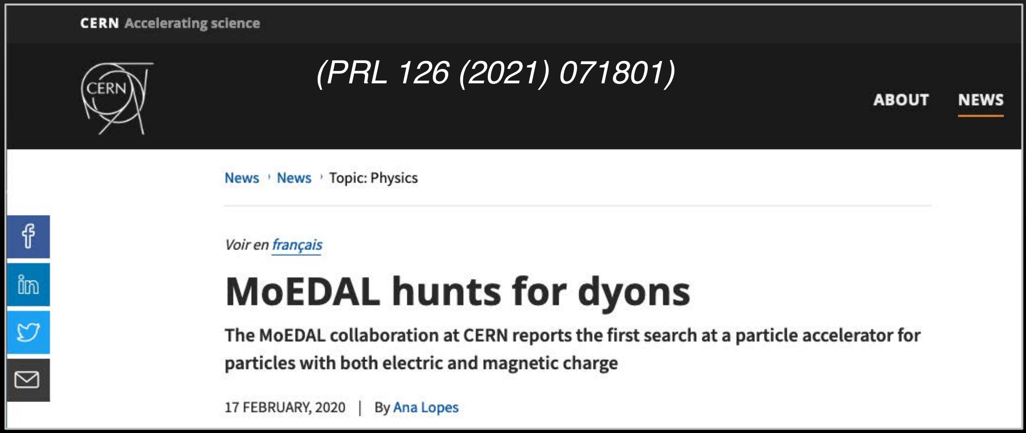
First Direct Search for the Dyon



Predicted by Schwinger in 1969 a dyon has electric &magnetic charge

- *Mass limits 750-1910 GeV were set for dyons with ≤5g_D & electric charge ≤ 200e*

First ever explicit search for a dyon


CERN Accelerating science

(PRL 126 (2021) 071801)

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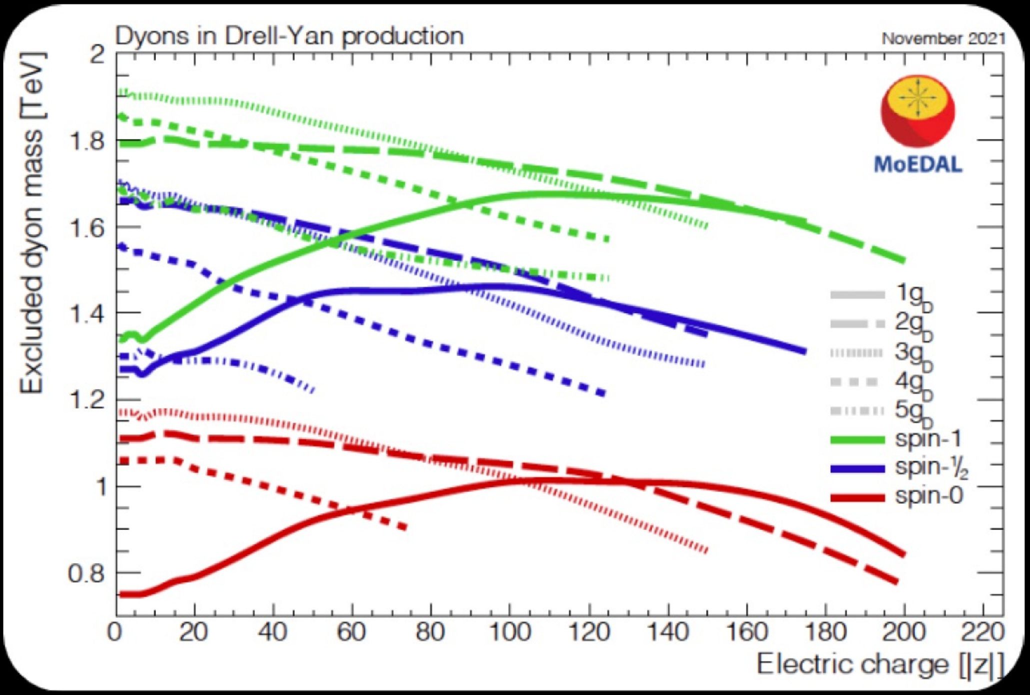
Voir en français

MoEDAL hunts for dyons

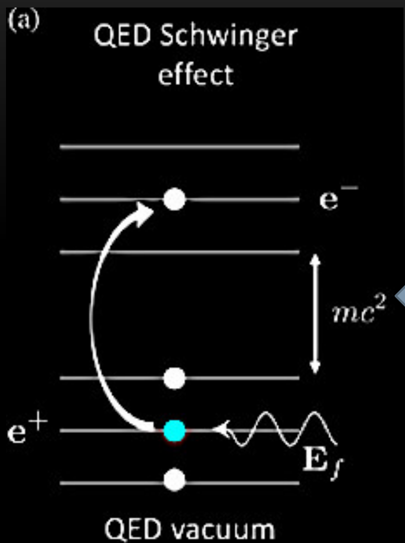
The MoEDAL collaboration at CERN reports the first search at a particle accelerator for particles with both electric and magnetic charge

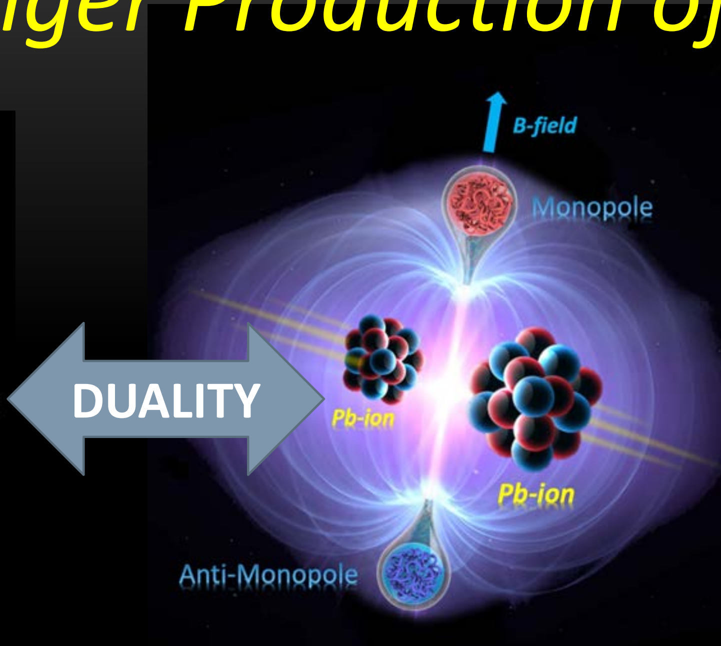
17 FEBRUARY, 2020 | By Ana Lopes

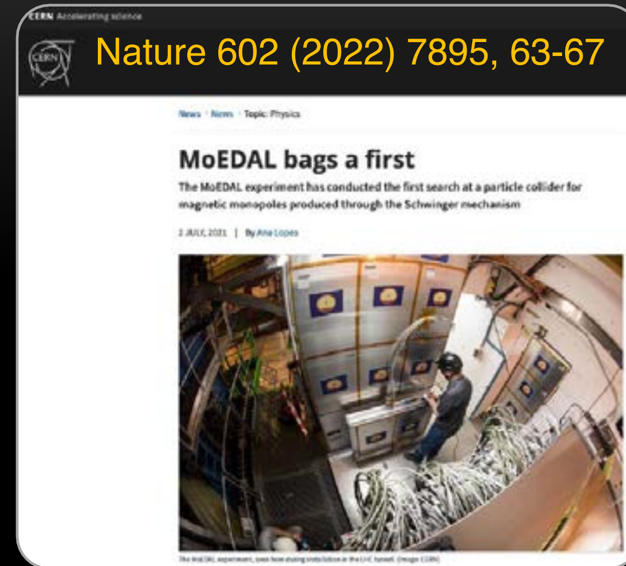


Schwinger Production of Monopole Pairs

MAPP
MoEDAL







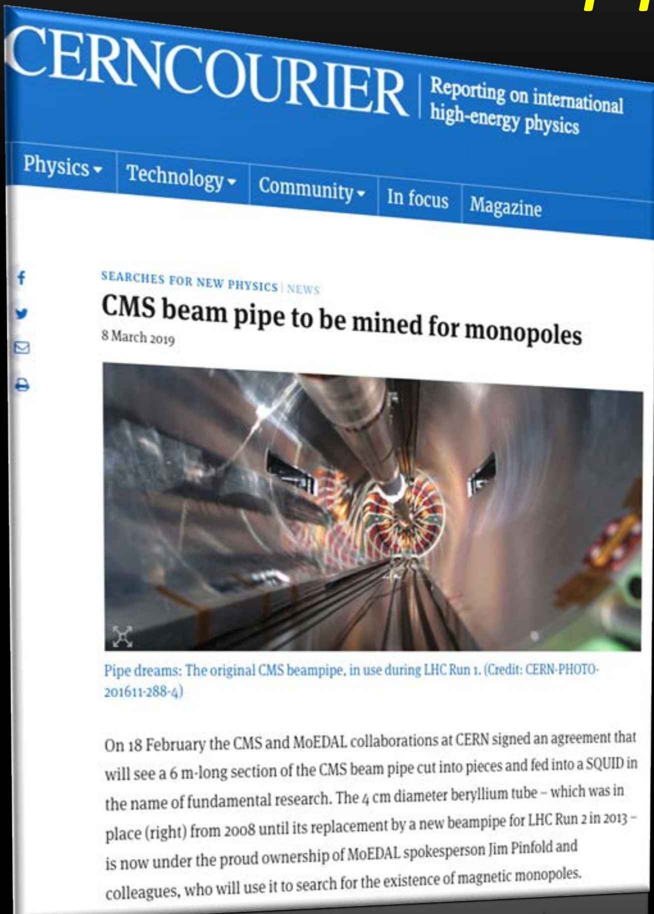
Pair production of electron-positron pairs in a very strong electric field

Pair production of monopole-antimonopole pairs in a very strong magnetic field created in ultraperipheral "collisions" of Pb-ions at the LHC can be as much as 10^{16}T.

- ***Limits on Schwinger monopoles of 1 – 3 g_D and masses up to 75 GeV***
- *Advantages of Schwinger monopole production:*
  - *X-section calculation does not suffer from perturbative nature of coupling;*
  - *No exponential suppression for finite-sized monopoles.*

1st time finite sized monopoles detectable?

MoEDAL's Search for Monopoles Trapped in CMS Beampipe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SEARCHES FOR NEW PHYSICS | NEWS

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.

On Feb 2019: CMS officially transferred ownership of Run-1 CMS beampipe to MoEDAL

- MoEDAL searched for highly charged (up to 12 g_d) magnetic monopoles trapped in the Run1 CMS beampipe
  - Also useful in the search for Schwinger produced monopoles.
- We used the MoEDAL's SQUID detector based at ETH Zurich

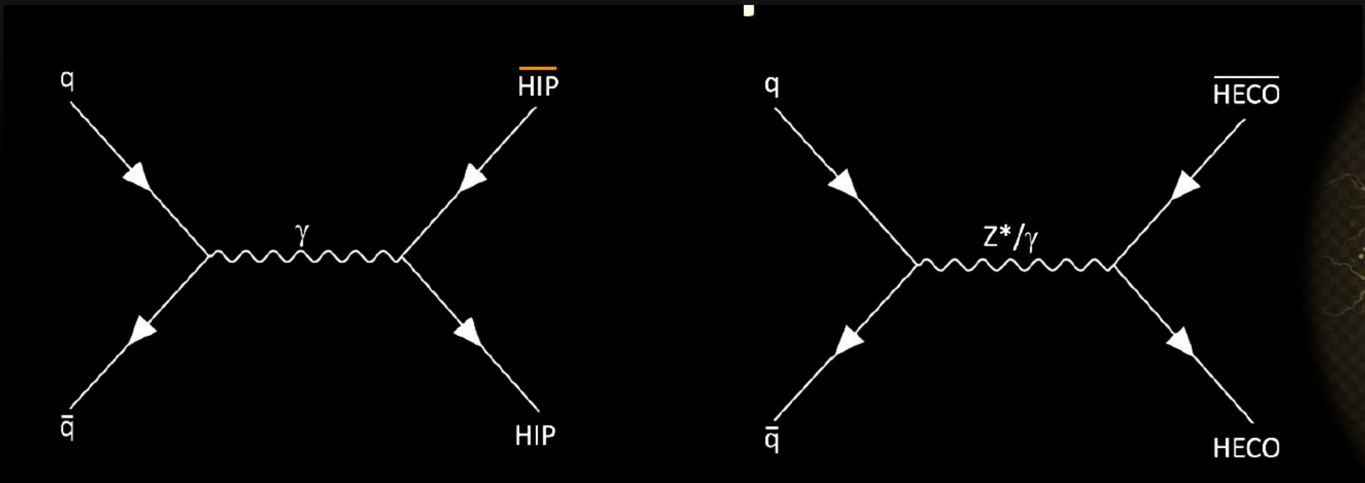
$$\Delta I = \frac{4\pi N}{L} g_D$$

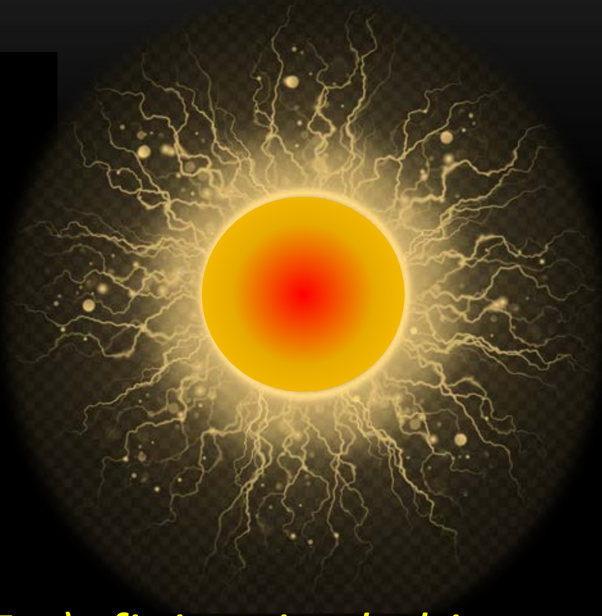
Signal for a monopole is a continuing current in the SQUID after the monopole has passed through

- Analysis of the beampipe is underway

Searching for HECOs

[Highly Electrically Charged Objects (HECOs)]

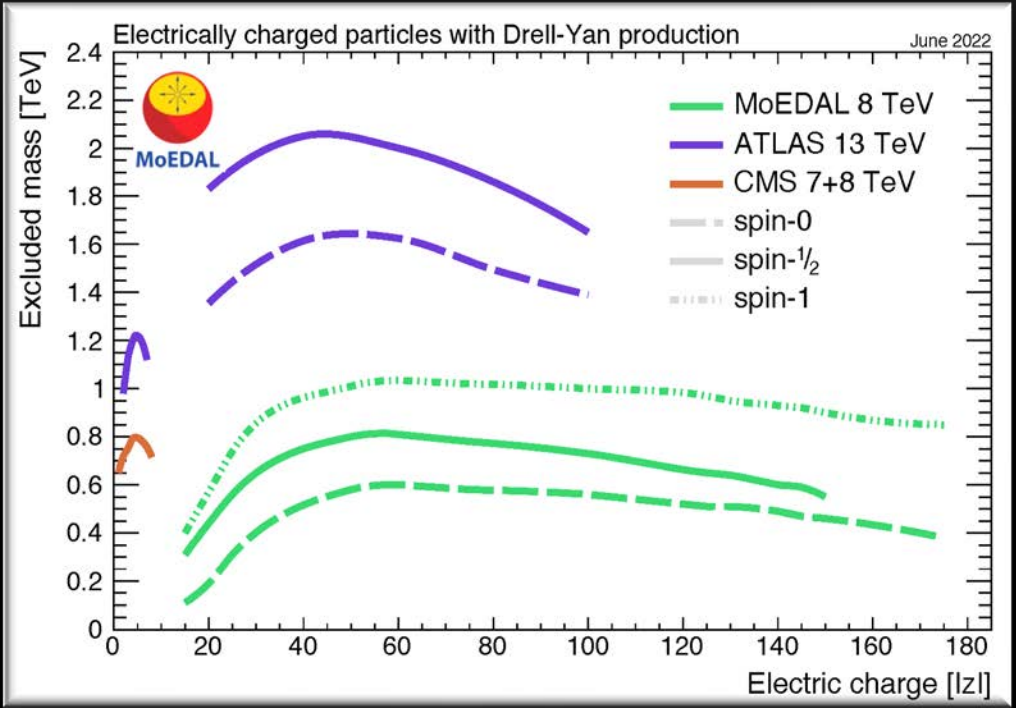




- *Highly Electrically Charged Objects (HECOs, Q > ~5e): finite-sized objects (Q-balls), condensed states (strangelets), microscopic black holes (through their remnants),etc.*
- *Drell-Yan production:*
  - *Z exchange is taken into account for fermions [Song, Taylor, J.Phys.G 49 (2022) 045002]*
  - *Mon-perturbativity of large coupling can be tackled by appropriate resummation [Alexandre, Mavromatos, in progress*

HECO Limits to Date

- *The MoEDAL prototype detetector at Run-1 set limits on HECOs with charge in the range 15e – 175e & masses from 110 – 1020 GeV*
- *Run-2 result out in a month or so with full MoEDAL detector, larger LUMI ,and higher E_{cm} ➔much superior mass and charge limits*



World's best charge limits on HECOs

Eur.Phys.J.C 82 (2022) 8, 694,
e-Print: 2112.05806 [hep-ex]

New Physics with Charge 1e—10e

MAPP
MoEDAL

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

Figure of merit for large energy loss: ***z/β***

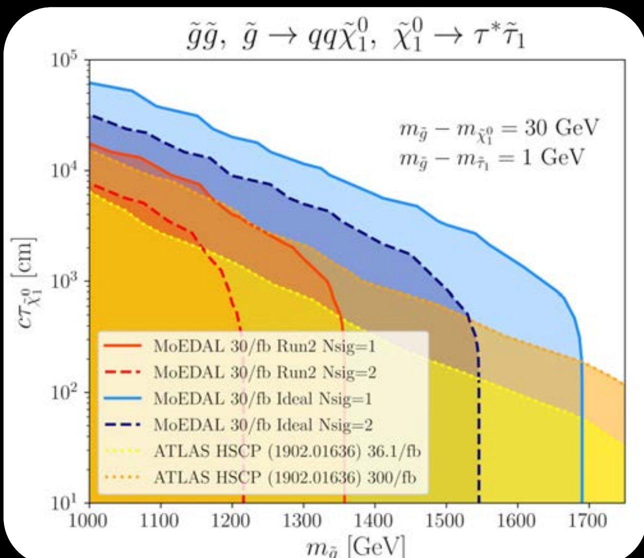
MoEDAL detector optimised for HIP discovery with a detection threshold as low as ***z/β* = 5**

Ionization enhanced by lower velocity - MoEDAL is sensitive to single electric charge when $\beta < 0.15c$

- *MoEDAL is background-free experiment → discovery scenarios require 1, 2 or 3 signal events*
- *Integrated luminosities at IP8 (LHCb/MoEDAL)*
  - *Run-3 increase in instantaneous luminosity by a factor of 5 → 30 fb^{-1}, roughly 10 times less than ATLAS & CMS*
  - *High Luminosity LHC (HL-LHC) → 300 fb–1*

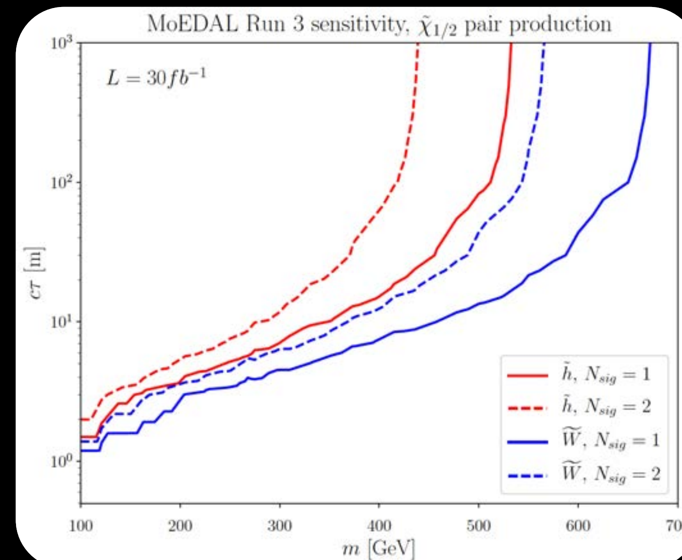
Detecting Long-lived SUSY Partners

- Supersymmetric charged long-lived states: sleptons, R-hadrons, charginos plus doubly charged higgsinos in L-R symmetric models
  - With no trigger, timing and SM backgrounds, MoEDAL can relax selection requirements & increase sensitivity to charged long-lived SUSY particles



EPJC 80 (2020) 431 — sleptons

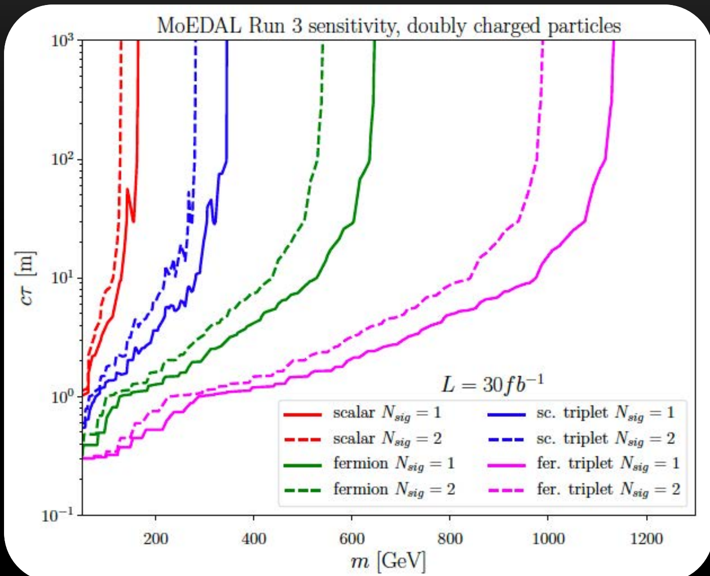
MoEDAL covers long-lifetime region in Run 3 for gluinos, stops, sleptons and charginos



EPJC 80 (2020) 572 — charginos

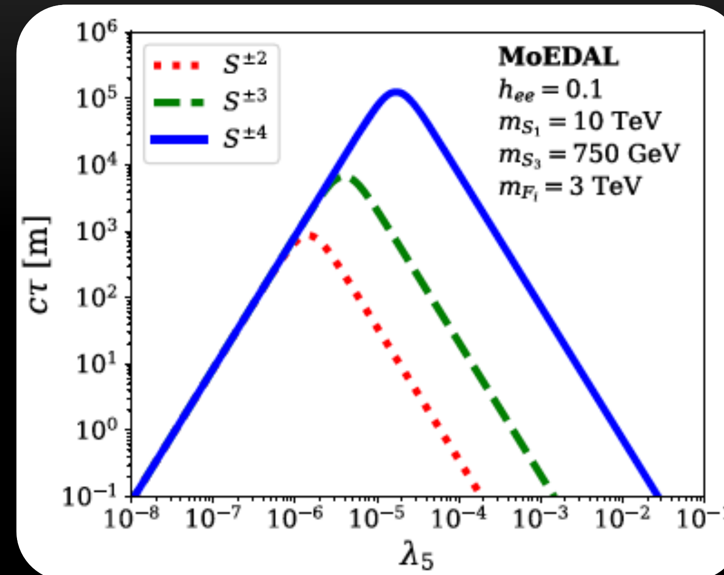
- Benchmark decay chain: $\tilde g \tilde g$ production with: $\tilde g \to jj\tilde\chi_1^0$, $\tilde\chi_1^0 \to \tau^\pm \tilde\tau_1$
  - $\tilde\chi_1^0$ moderately long-lived ➜ decays in tracker
  - $\tilde\tau_1$ charged & long-lived ➜ interacts with detector

Multiply Charge Particles - Model Specific



EPJC 80 (2020) 572

MoEDAL can cover long-lifetime region in Run 3 and HL-LHC

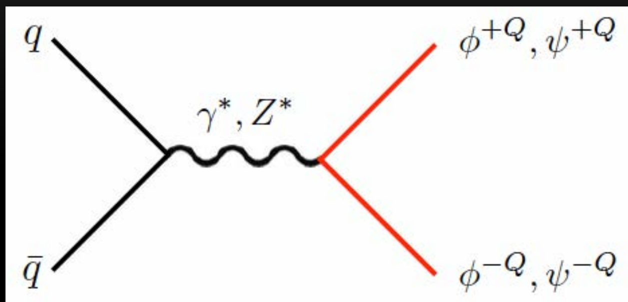


EPJC 81 (2021) 697

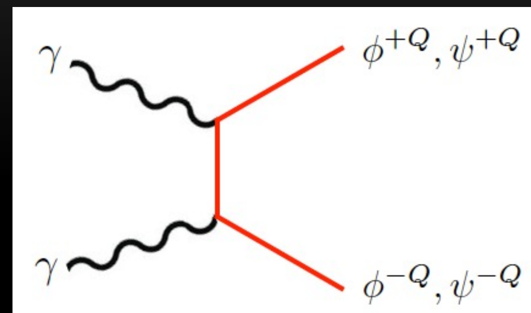
- *Doubly charged particles:*
  - *Predicted in L-R symmetric models, seesaw neutrino models, little Higgs models, … (+ SUSY extensions), extra dimensions …models considered: (scalar, fermion) × ($SU(2)_L$ representations: singlet, triplet)*
- *2e, 3e, 4e states occur in some radiative neutrino mass models - In this class of models, the SM is extended with two scalar fields, S_1 and S_3 , which are singlet and triplet representations of SU (2)L*
  - *Long-lived due to small neutrino mass and high electric charge*

Multiply Charged Particles – Generic Case

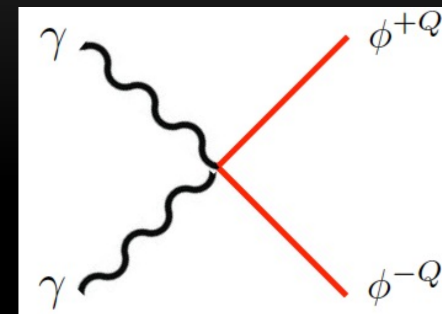
arXiv:2204.03667v1 [hep-ph] 7 Apr 2022



s-channel (Drell-Yan)



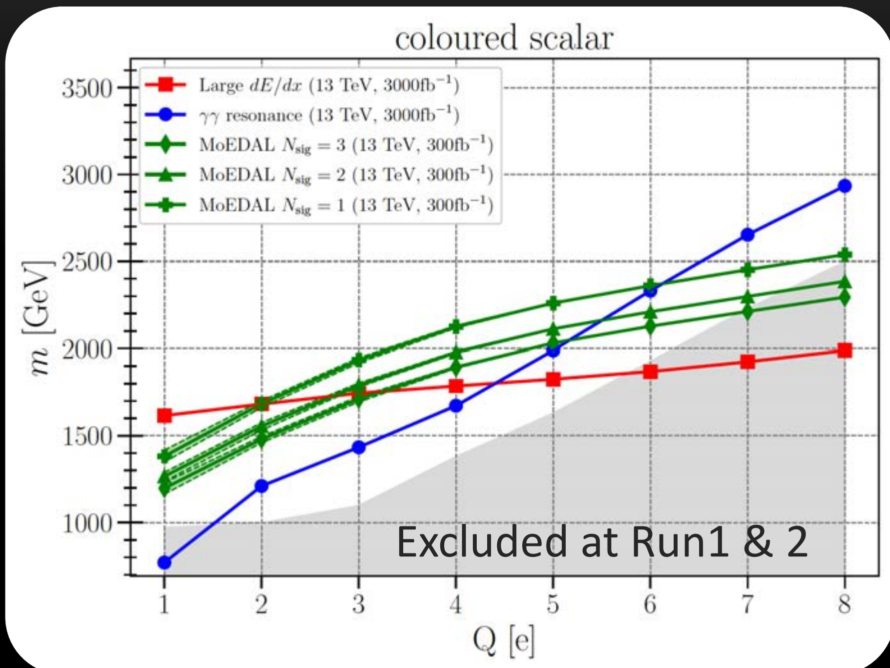
t-channel γγ fusion

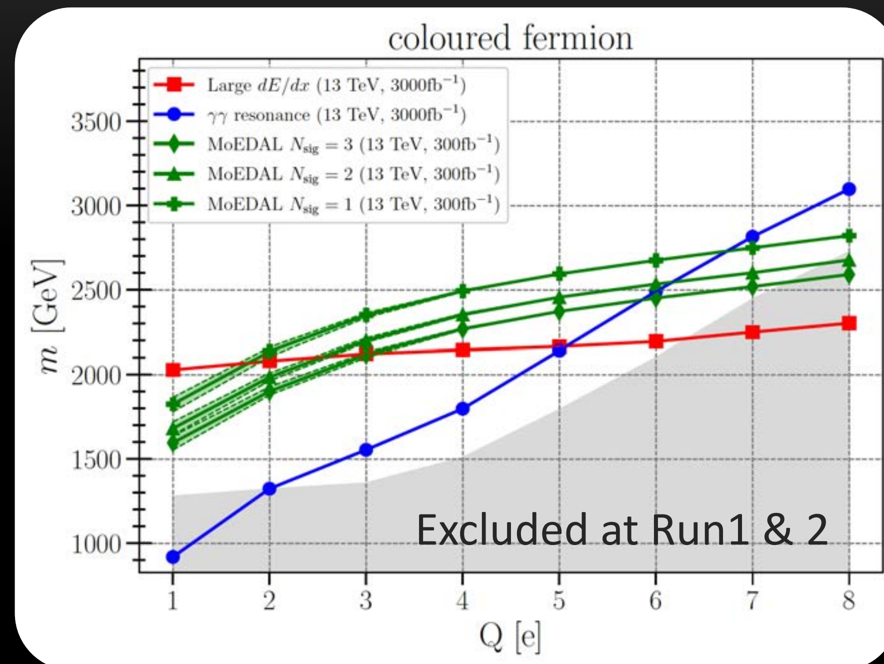


seagull γγ fusion (scalar only)

- *Phenomenological study independent of underlying model -most searches only assume DY but for high charges, photon contributions become very relevant*
  - *Considering particles with spin 0 and 1/2, with electric charges in range $1 \leq |Q/e| \leq 8$, which are singlet or triplet under SU(3)C.*
  - *Such particles might be produced as particle-antiparticle pairs and propagate through detectors, or form a positronium(quarkonium)-like bound state.*

MoEDAL vs. ATLAS/CMS





- *MoEDAL has the best sensitivity at intermediate charges at HL-LHC & the best overall sensitivity that doesn't rely on diphoton resonance detection*
  - *ATLAS/CMS direct detection based on searches for large dE/dx → better sensitivity at low charges*
  - *ATLAS/CMS searches for diphoton resonances has better coverage at high charges*

Phase-1: MoEDAL + MAPP-1 at LHC's Run-3 (2022-2024?)

The Search for FIPs

The Search for LLPs

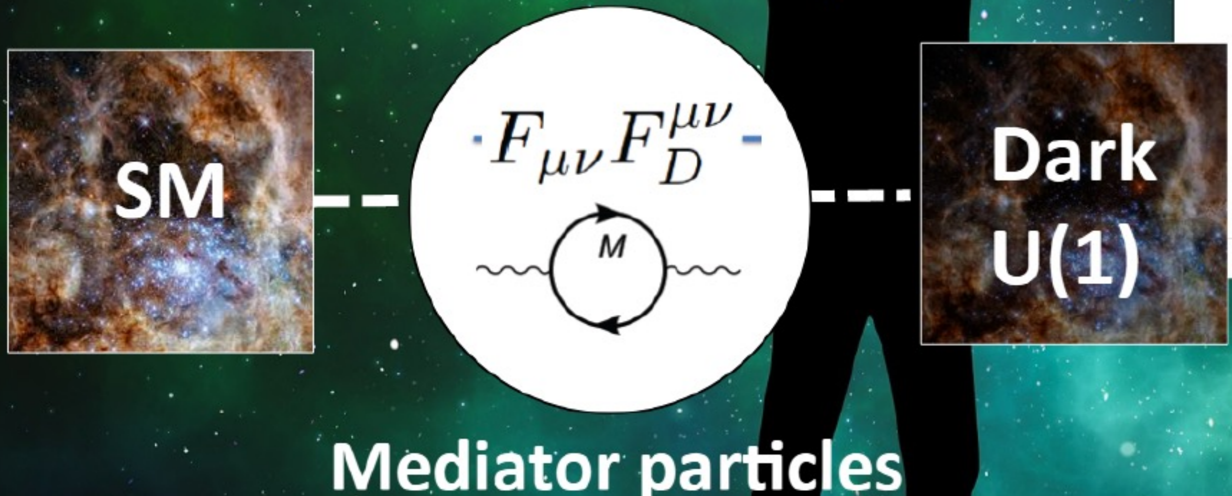
The Search for HIPs

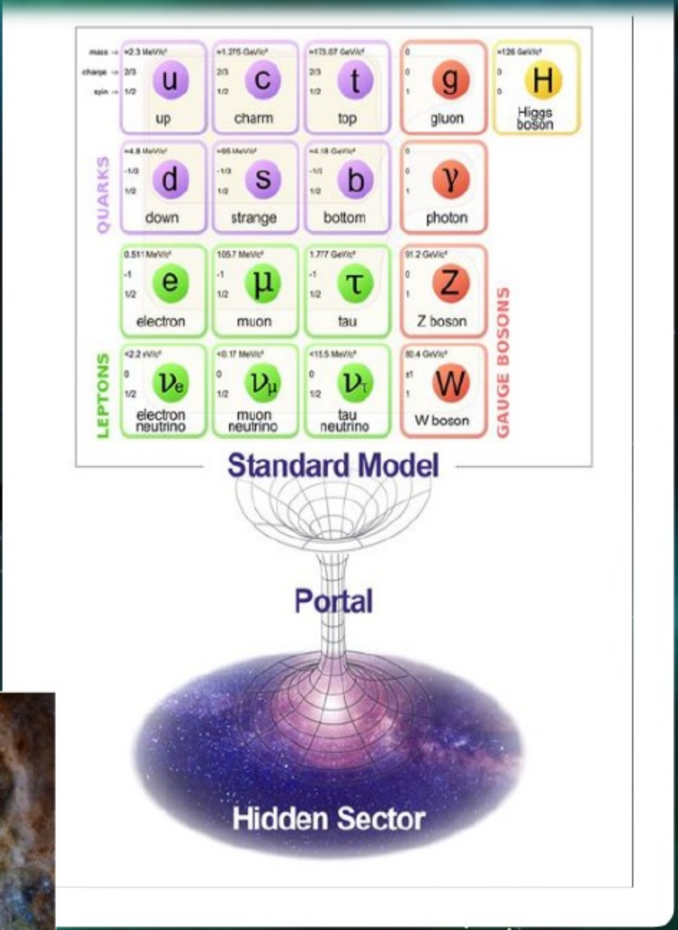
MAPPing the Dark Sector

The main evidence for dark matter is gravitational. What are the "likely" non-gravitational interactions?

To detect a dark sector, we must know how it interacts with us.

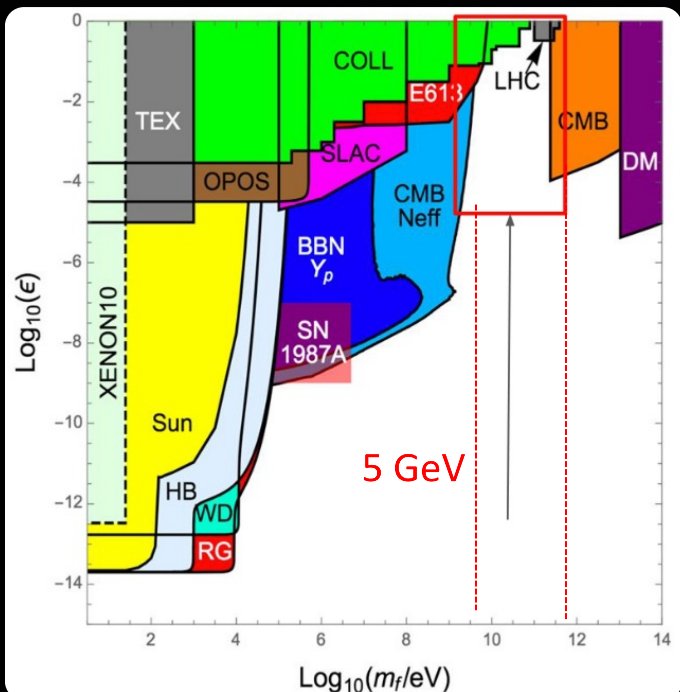
- *Interactions between the two sectors are via mediator particles through so-called "portal interactions" — in this case, the vector portal:*





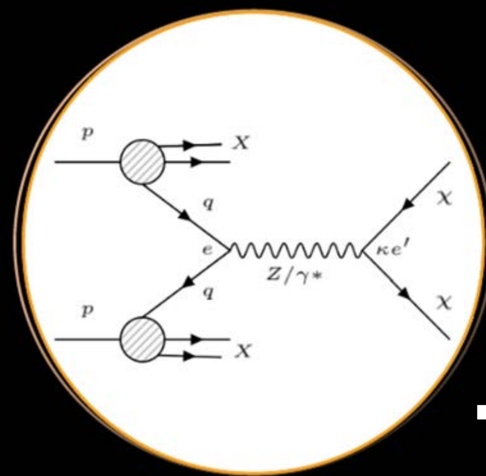
Production of Milli-charged at Colliders

mCPs arise naturally from the dark sector eg via the Vector Portal/Dark Photon



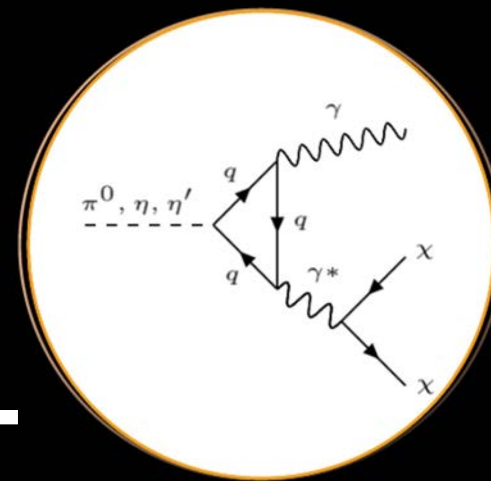
The Sweet Spot

arXiv:1511.01122

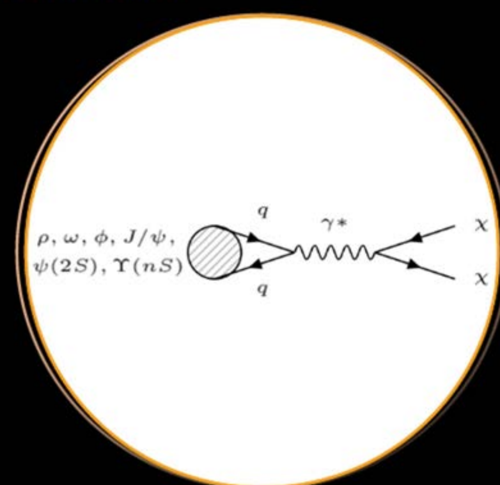


via the **Drell-Yan Process**

+

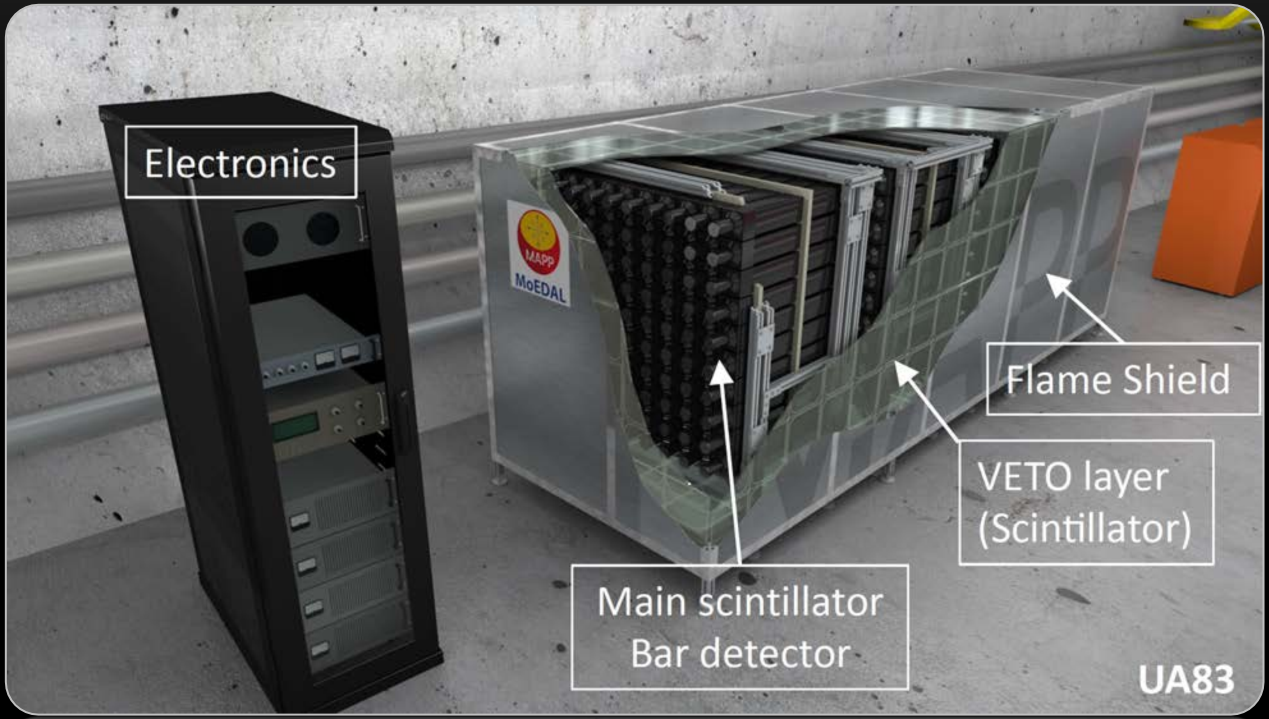


via **Dalitz decays of pseudoscalar mesons**



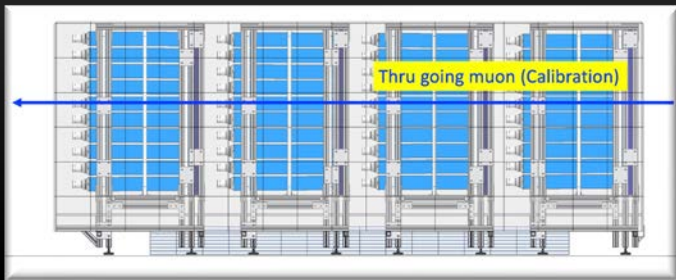
via **direct decays of vector mesons**

The MAPP-1 Detector



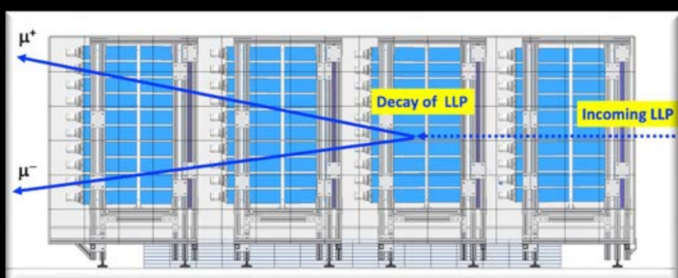
- *400 scintillator bars (10 x 10 x 75 cm^3) in 4 sections readout by PMTs - Protected by a hermetic VETO counter system*
- *Each through-going particle sees 3m of scintillator readout by a coincidence of 4 low noise PMTs*

MAPP – Modes of Detection

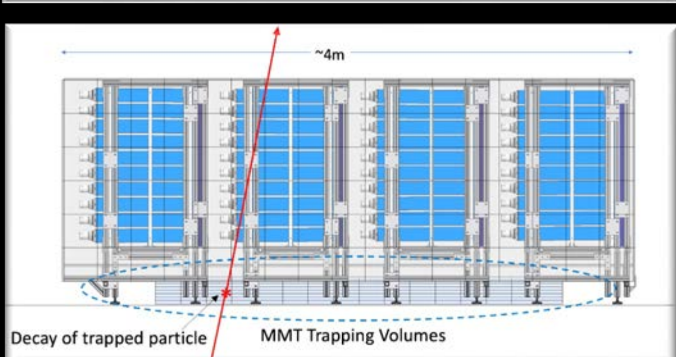


Muons from IP (Calibration)

Millicharged particle detection

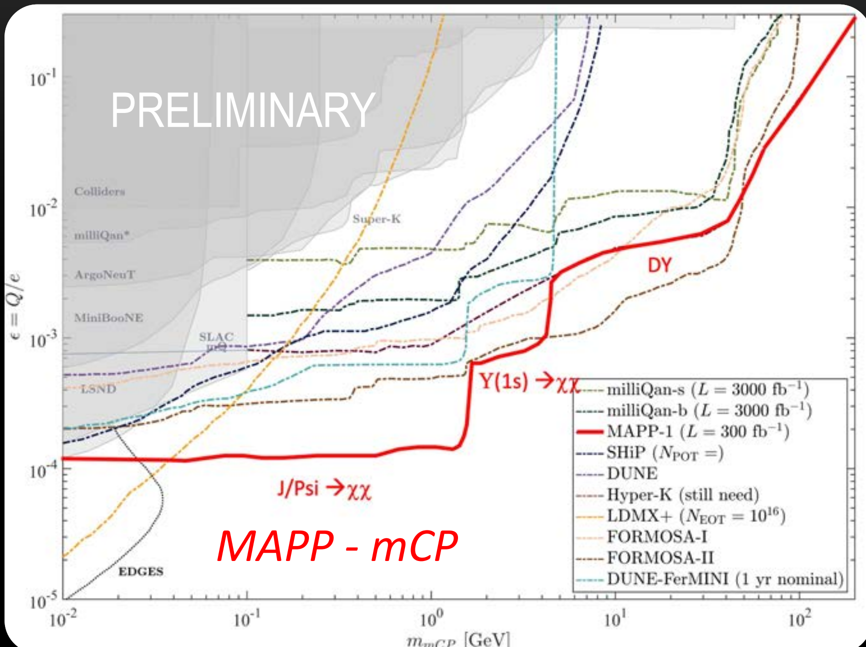


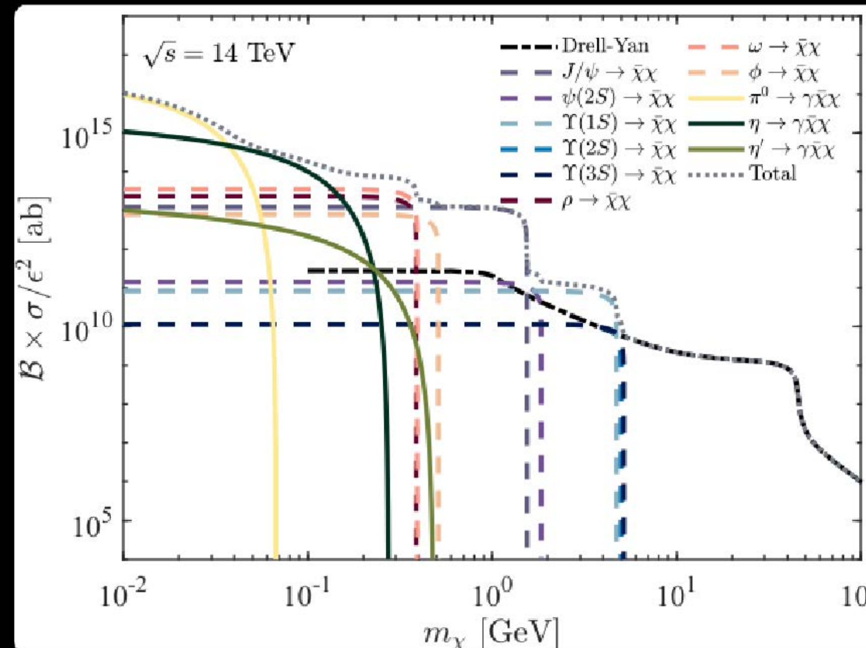
Neutral LLP Detection



Charged LLP Detection
(In conjunction with MoEDAL)

The MAPP-mQP Bar Detector Sensitivity



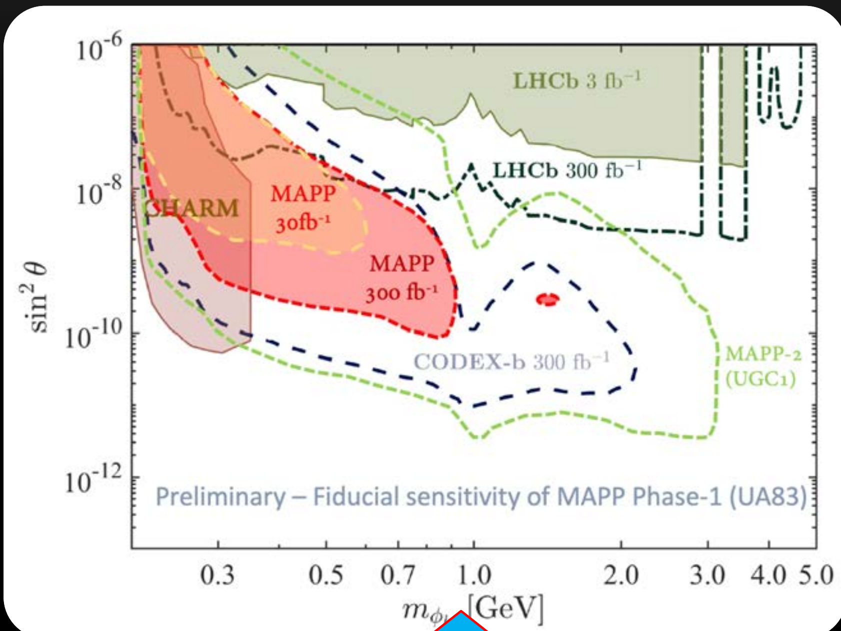


mCP Prod. X-secs for 14 TeV pp Collisions

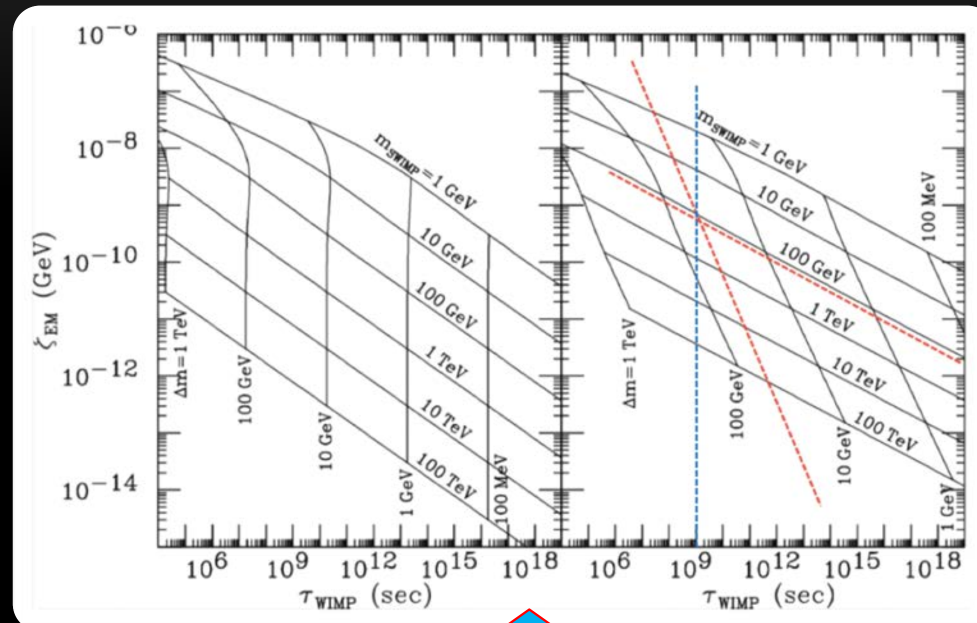
- *LEFT: Estimated reach of MAPP-mCP at √ s = 14 TeV for HL-LHC*
  - *We are planning an outrigger detector to enhance the DY sensitivity*
  - *We need to add in more channels(mostly meson decays that should also enhance our sensitivity further*
- *RIGHT: the addition of the resonances and meson decays to mCPs enhances the number of lower mass mCPs available to detect*
  - *CAVEAT: At present the MAPP-mQP plots assumes 100% detector eff.*

MAPP-1 LLP Sensitivity

Neutral LLPs



Charged LLPs



arXiv:2110.09392v1 [hep-ph] Oct 2021

Phys. Rev. D, 97:015023, Jan. 2018.

This benchmark involves the decay of dark Higgs where the dark Higgs mixing portal allows the exotic inclusive B decays, $B \to X_s\phi_h$, (ϕ_h is a light CP–even scalar that mixes with the SM Higgs) & $\phi_h \to \mu^+\mu^-$

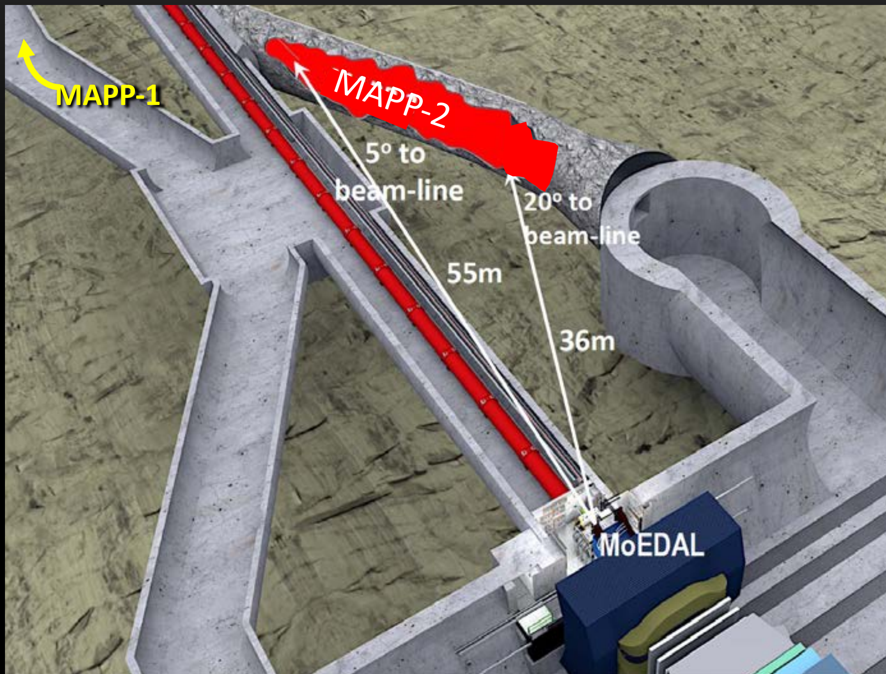
J. L. Feng, A. Rajaram Phys. Rev. D 68, 063504 (2003).

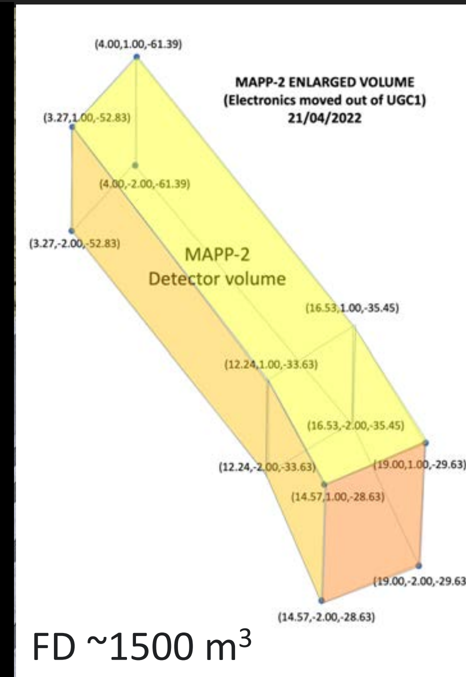
CDM made of super WIMPs, that inherit the desired relic density from late decays of metastable WIMPs. Predicted values of WIMP lifetime and EM energy release shown above

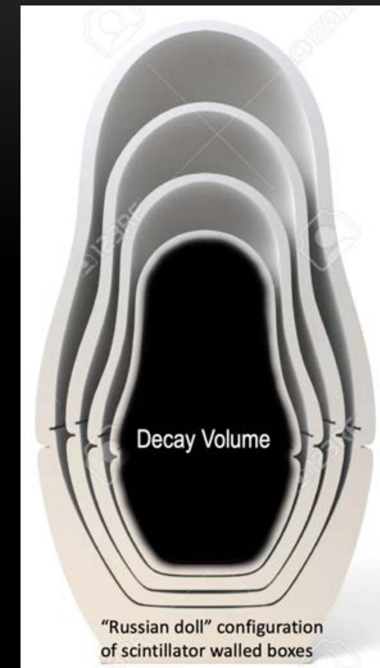
Sensitivity to Charged LLP lifetimes >10 yrs

Phase-2: the HL-LHC, MoEDAL+MAPP-1+MAPP-2 [2026 -2037?]

Phase-2: MAPP-2 for HL-LHC

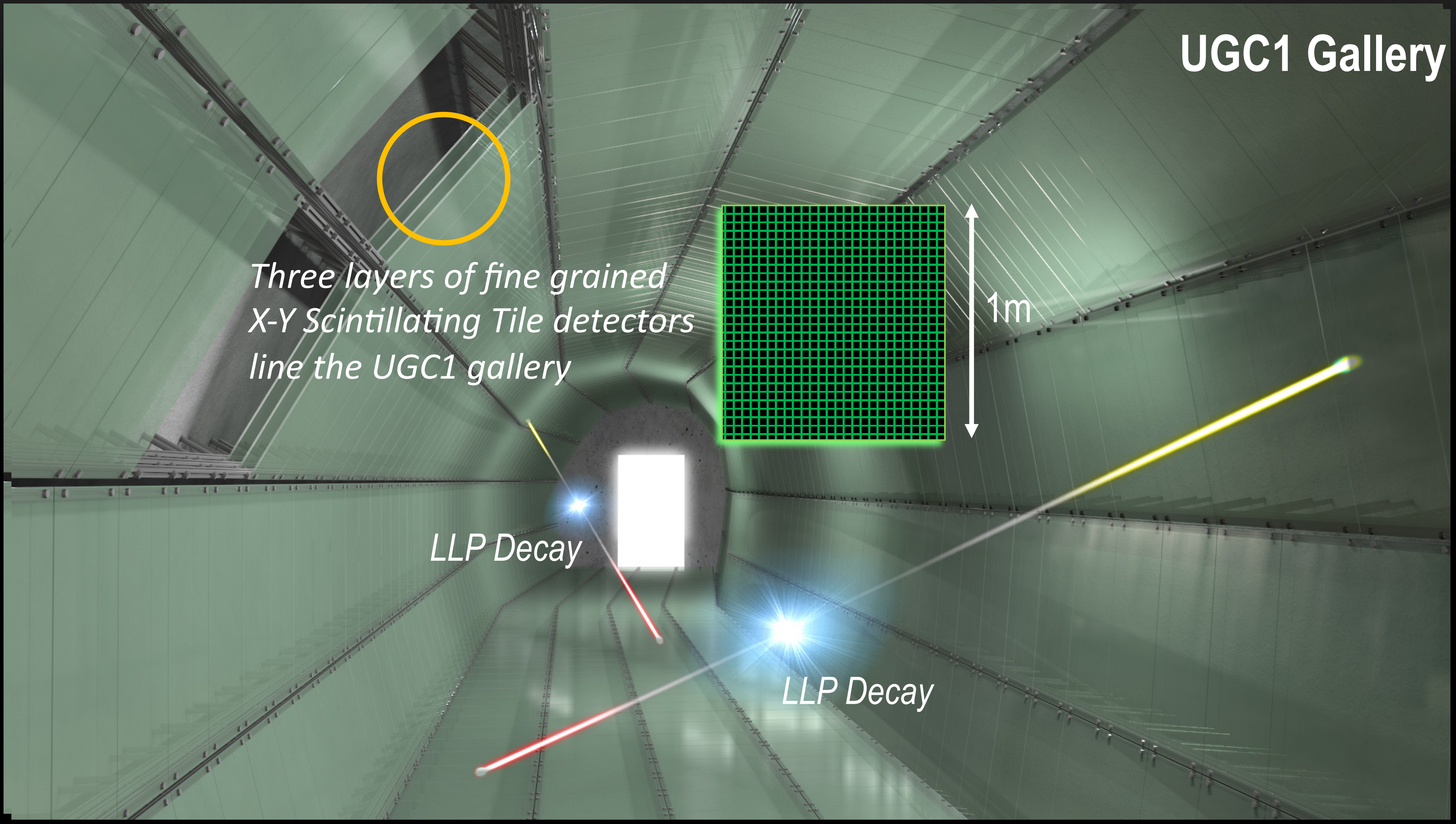






- *The UGC1 gallery would be prepared during LS3 prior to HL-LHC*
- *The MAPP-2 detector extends down the length of the UGC1 gallery*
- *The tracking detectors would form 3 or 4 hermetic containers - one within the other – lining the walls of UGC1*
  - *Detector technology large tiles with x-y WLS fibre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

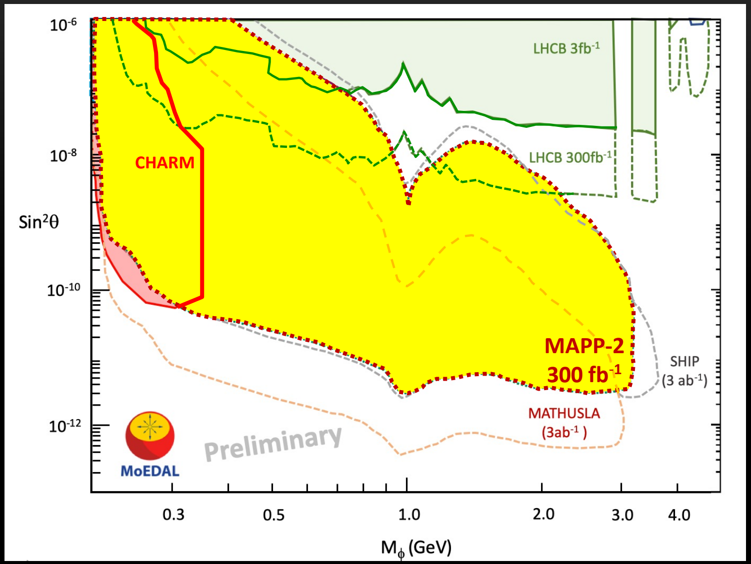
The MAPP-2 Detector Volume



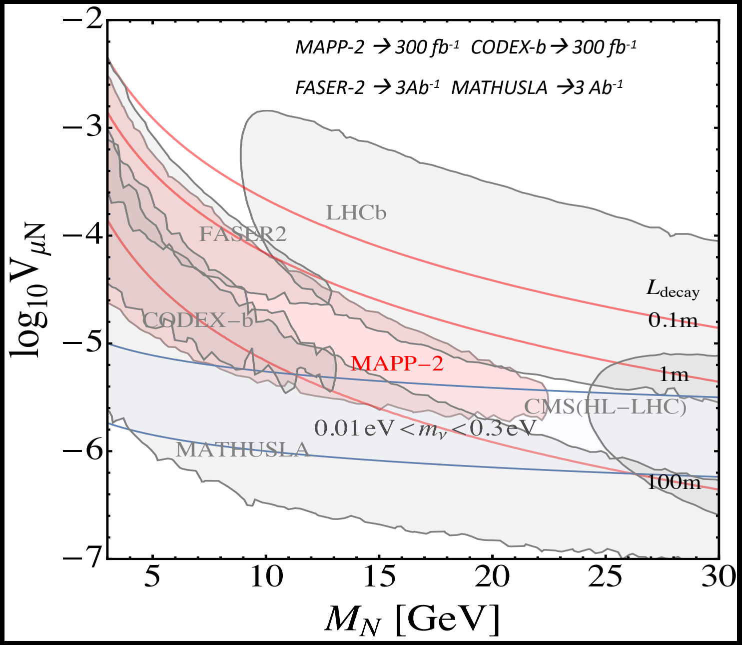
MAPP-2 ~1200 m^3 of instrumented decay volume. Estimated technical costs of MAPP-2 ~$5-6M including 0.5K of civil engineering.

MAPP-2 (LLP): Example Physics Studies

- *Benchmark process:*
  - *Where the Higgs mixing portal admits inclusive $B \rightarrow X_s \phi$ 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*
  - *Full Monte-Carlo simulation now available and being studied*



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



MoEDAL

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

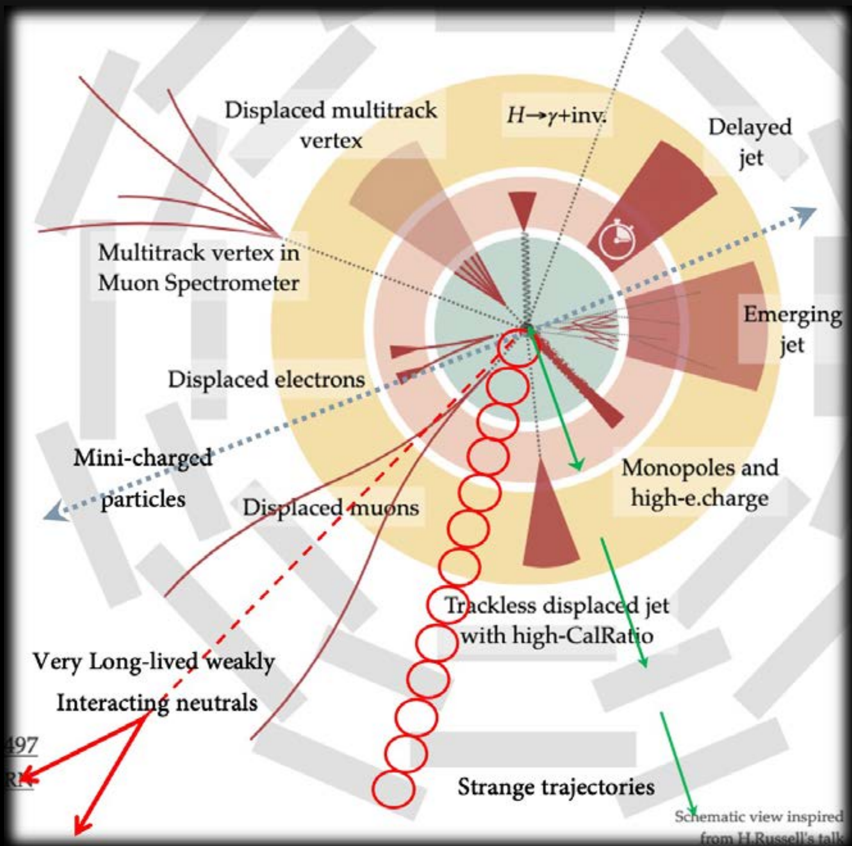
Dedicated search experiments such as MoEDAL-MAPP are the "new eyes" of the LHC

There are now some indications that our approach my be correct:

There is a hint of multiply charged particle production in ATLAS (ATLAS-CONF-2022-034) data and also the possibility that mini-charged particles can explain the EDGES anomaly (the detection of an anomaly in the 21-cm H absorption spectrum indicating more absorption than expected.)

EXTRA SLIDES

The Unconventional Signs of New Physics (for which ATLAS & CMS are not optimized)



Conventional collider detectors are not optimized for certain signatures of new physics

Mass < ~ 0.1 eV

Mass > ~180 GeV/c^2

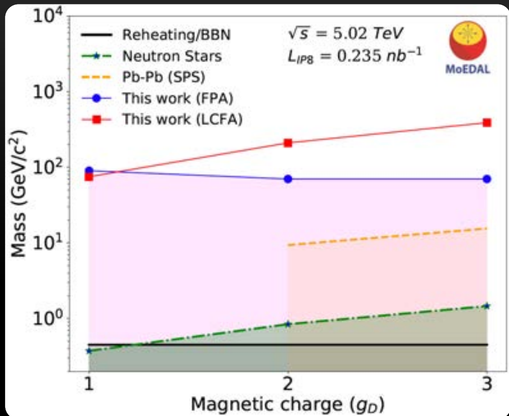
Lifetime ($c\tau$) > ~10m

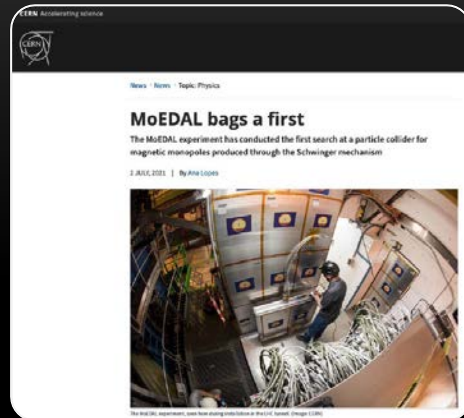
Fractional charge

Charge > 1 or Magnetic charge

CLEAR ATTRIBUTES OF NEW PHYSICS

The Importance of Schwinger Production





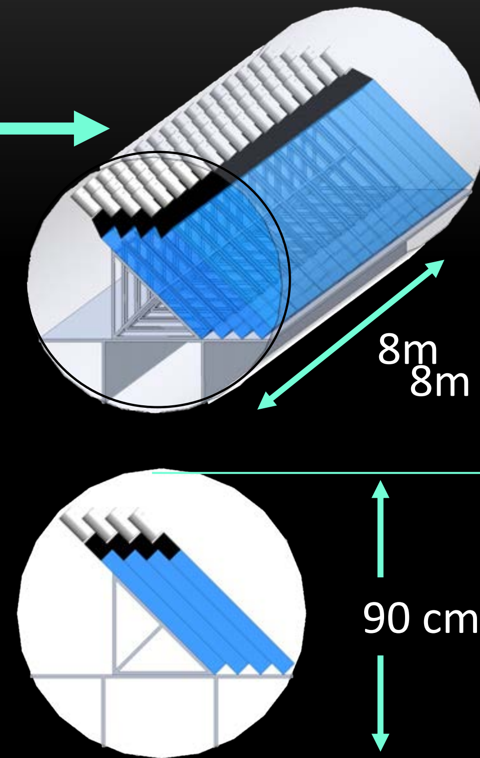
Nature 602 (2022) 7895, 63-67

Theory input: Gould, Ho, Rajantie, PRD 100, 015041 (2019), PRD 104, 015033 (2021) Ho & Rajantie, PRD 101, 055003 (2020), PRD 103 (2021) 11, 115033

- *Two approxs to the calculation of the overall MM production X-section*
  - *FPA (free-particle approximation): spacetime dependence of EM field of the heavy ions is treated exactly, but MM self-interacti... neglected MM*
  - *LCFA (locally ... e to the FPA*
  - *Limits on mo... eV*
- *Advantages ove... on:*
  - *X-section calculati... s not suffer from non perturbative nature of coupling*
  - *No exponential suppression for finite-sized MMs*
- *Probably the 1st time that finite sized MMs would have been detectable.*

First ever search for Schwinger Produced monopoles

The Outrigger Detector Upgrade



- *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 larger "millicharges."*
  - *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*