MoEDAL-MAPP, an LHC Dedicated Search Detector Facility

MoEDAL-MAPP, an LHC Dedicated Detector Search Facility (Sep 8, 2022) Contribution to Snowmass 2021 e-Print: 2209.03988 [hep-ph]. Submitted to EPJ-ST

James L. Pinfold
University of Alberta
For the MoEDAL-MAPP Collaboration

Corfu 2023 Summer Institute workshop on Future Accelerators.

John Kapodistrias

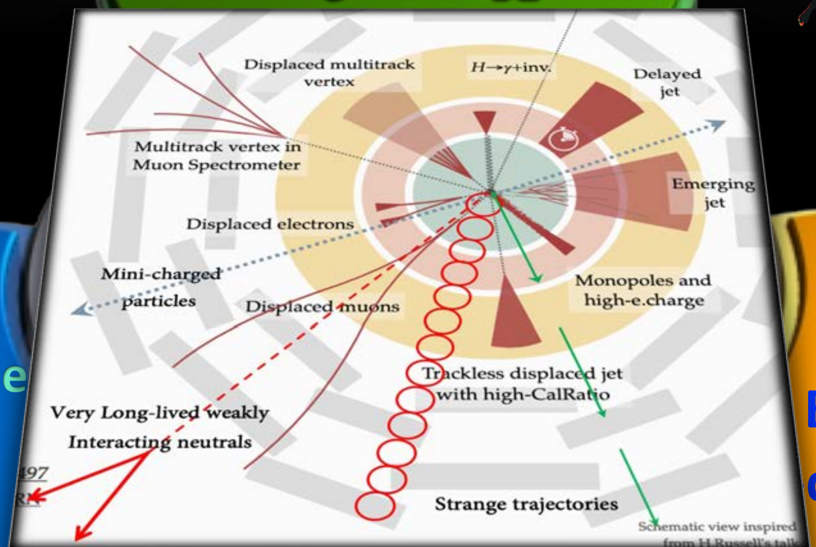
Where is the New Physics?

Avatars of New Physics…….

Long-lived Particles (LLPs)

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

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



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
$dE/dx \propto Z^2/\beta^2$
$Z(<<1) \; \beta(\sim 1)$

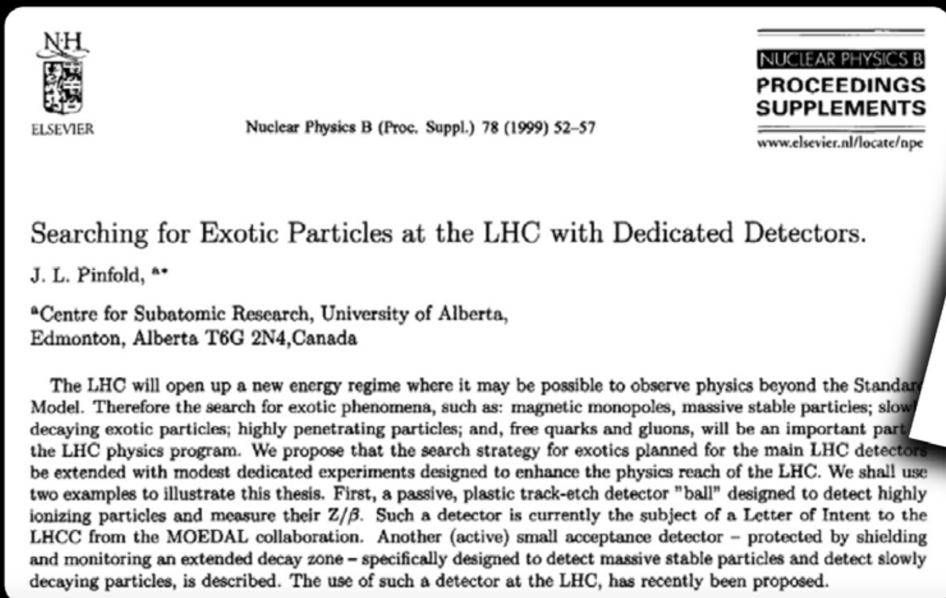
Feebly interacting particles (FIPS)

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

The MoEDAL-MAPP Philosophy

MAPP
MoEDAL

MoEDAL the 1st Dedicated Search Experiment at the LHC



NH
ELSEVIER

Nuclear Physics B (Proc. Suppl.) 78 (1999) 52–57

NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS
www.elsevier.nl/locate/npe

Searching for Exotic Particles at the LHC with Dedicated Detectors.

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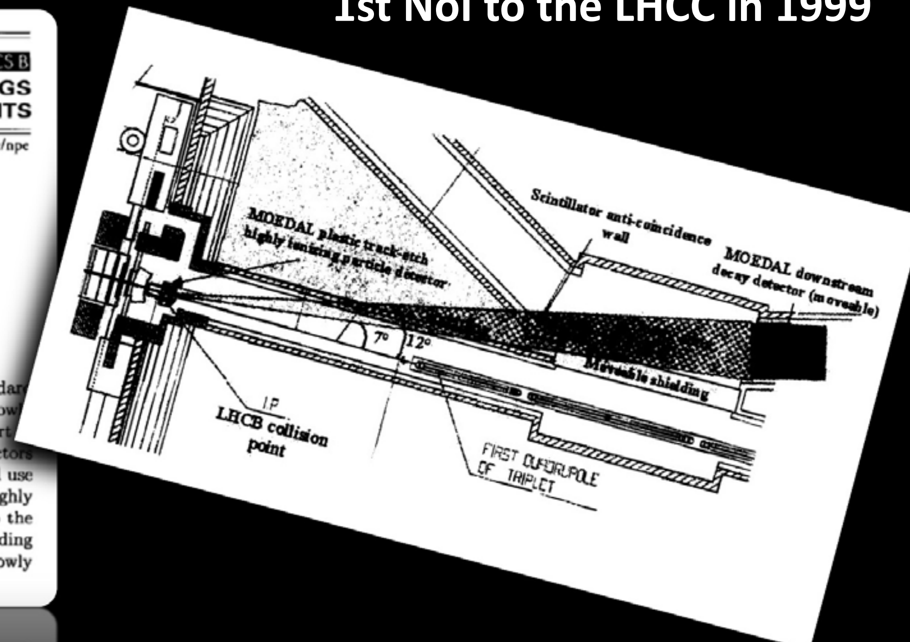
The LHC will open up a new energy regime where it may be possible to observe physics beyond the Standard Model. Therefore the search for exotic phenomena, such as: magnetic monopoles, massive stable particles; slowly decaying exotic particles; highly penetrating particles; and, free quarks and gluons, will be an important part of the LHC physics program. We propose that the search strategy for exotics planned for the main LHC detectors be extended with modest dedicated experiments designed to enhance the physics reach of the LHC. We shall use two examples to illustrate this thesis. First, a passive, plastic track-etch detector "ball" designed to detect highly ionizing particles and measure their Z/β. Such a detector is currently the subject of a Letter of Intent to the LHCC from the MOEDAL collaboration. Another (active) small acceptance detector – protected by shielding and monitoring an extended decay zone – specifically designed to detect massive stable particles and detect slowly decaying particles, is described. The use of such a detector at the LHC, has recently been proposed.

1st NoI to the LHCC in 1999

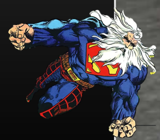


Dedicated Search Experiments (DSE):

- *They concentrate on some particular clear experimental signature of new physics*
- ***Their physics reach is largely complementary to the main detectors ATLAS & CMS***
- *They are usually stand alone, smaller & needs-be lower cost with small teams (<100)*

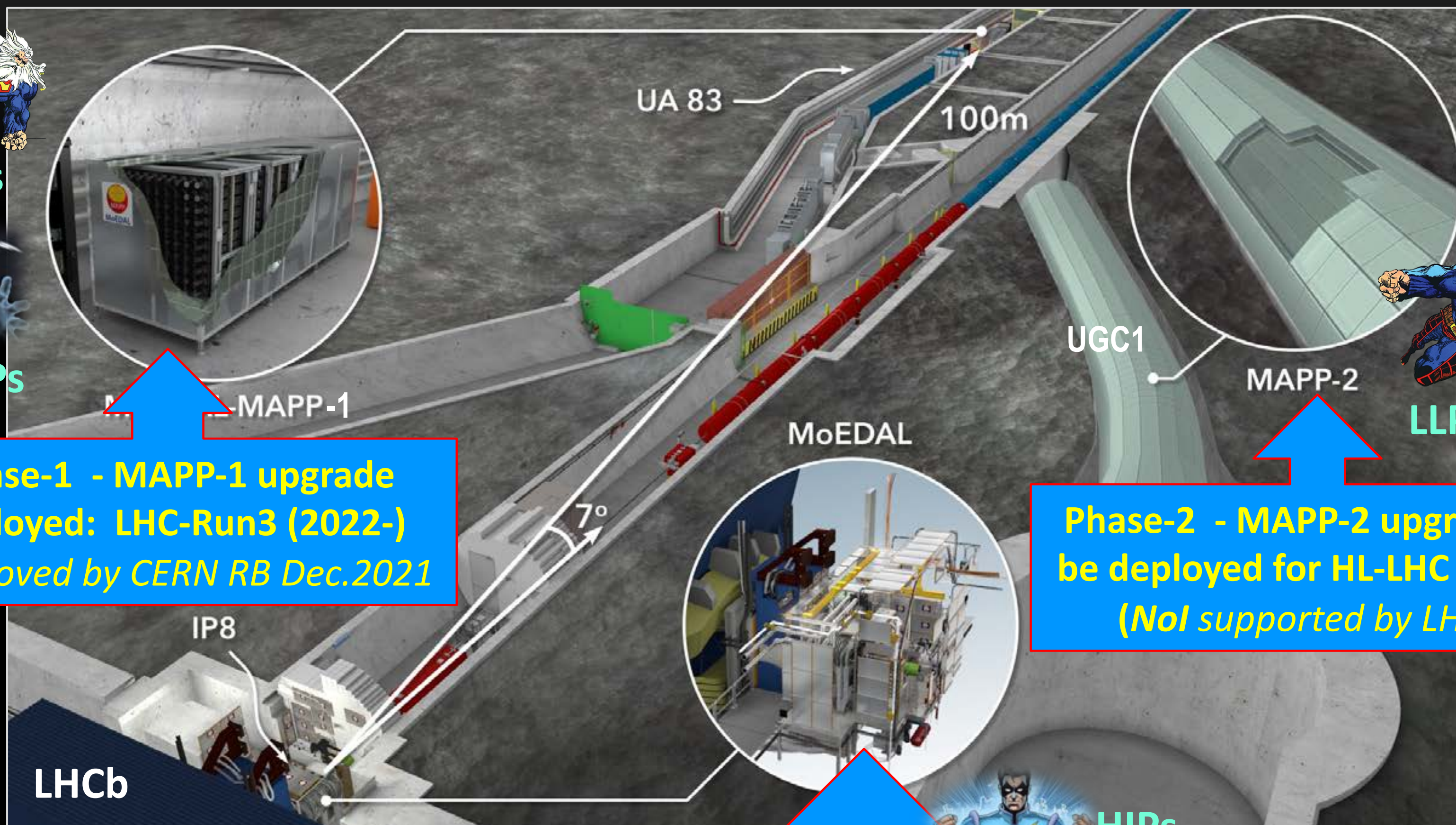
The DSE paradigm sees the LHC as a particle source observed by many experiments sensitive to the LHCs' multi-messengers of new physics

MoEDAL-MAPP a > 25 Year Project



LLPs

FIPs



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

LLPs

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

HIPs

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

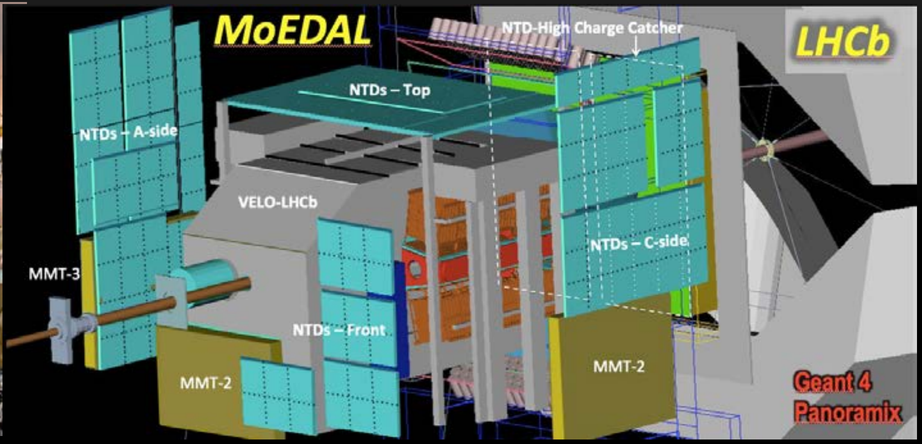
MAPP
MoEDAL

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

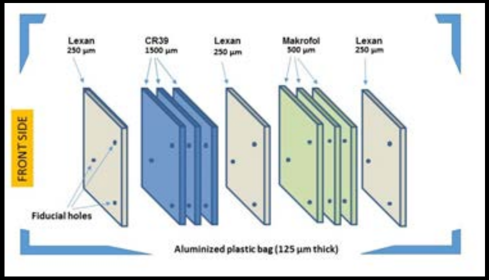
The Search Highly Ionizing Particles (HIPs)

The Phase-0 MoEDAL Detector

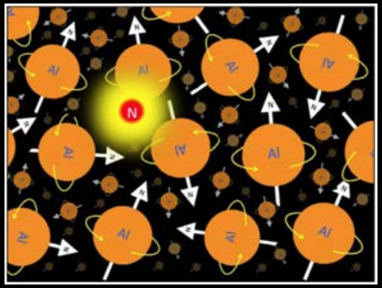
*Started data taking in (2011)2015– **the LHC's first dedicated search expt.***



--------Detector Technology at the IP --------



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

NO TRIGGER | **NO SM BACKGROUNDS** | **PERMANENT RECORD**

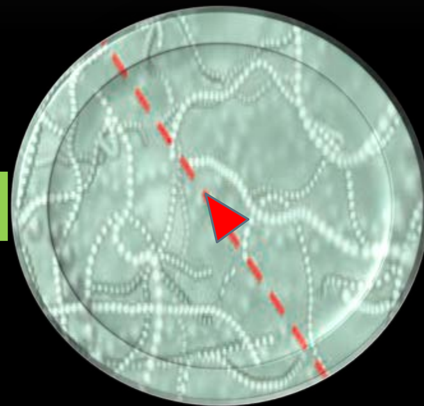
MoEDAL

MoEDAL's Remote Detector Facilities

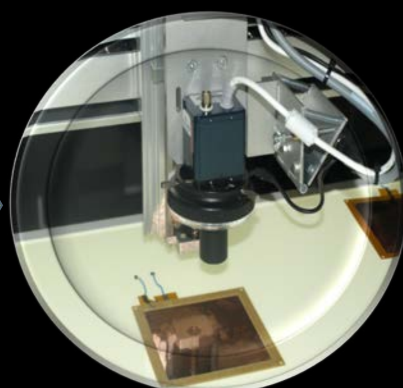
NTD Processing - INFN Bologna

Etching in hot sodium Hrdroxide reveals damage

HIP causes damage Zone In NTD plastic



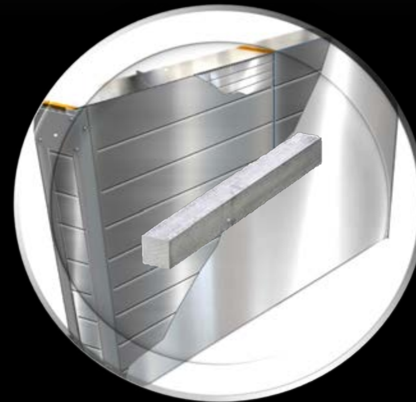
Etch pits reveal path and charge of HIP



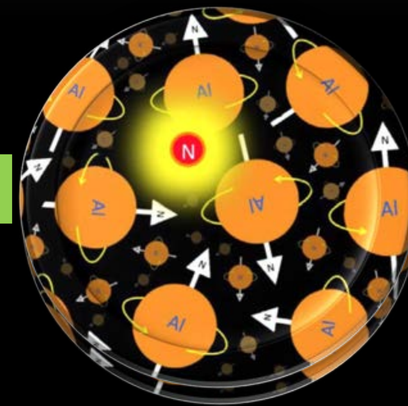
Etch pits measured by optical microscope

MMT Scanning- ETH Zurich

Trapping volumes are Removed for scanning



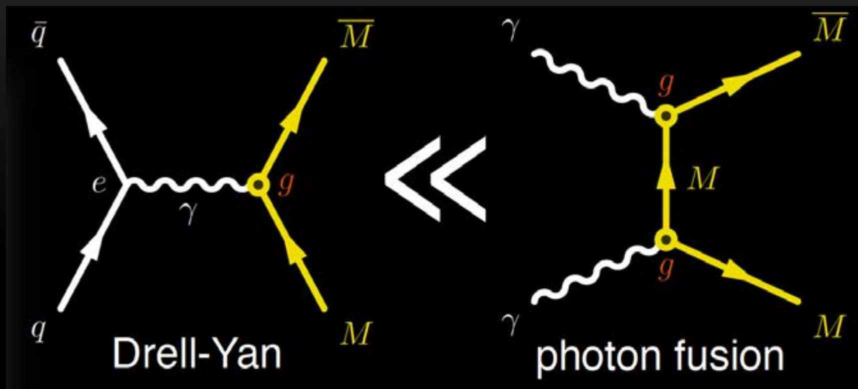
Monopole is trapped



Trapping volumes are Passed through a SQUID

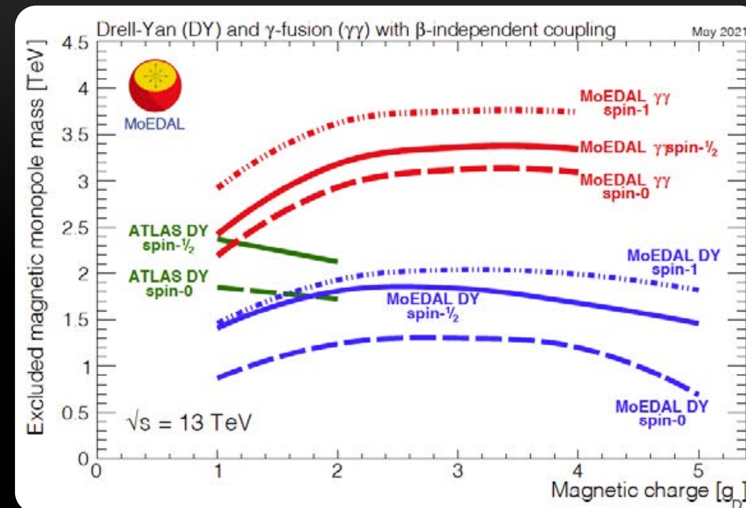
Monopoles cause a stable current in the SQUID

MoEDAL's Monopole Searches

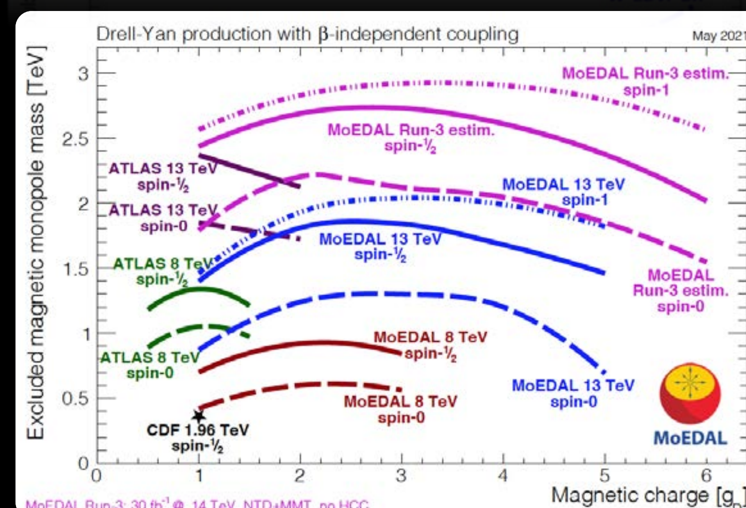


- *Unique features of MoEDAL's Search for Monopoles at the LHC*
  - *We consider β-dep./indep. couplings*
  - *Spin-1 monopoles*
  - *γγ fusion*
- *More results from Run-3 & HL-LHC*

MoEDAL has set the world's best monopole mass limits

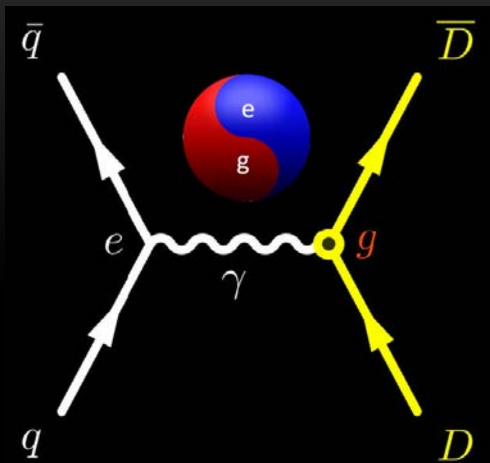


JHEP 1608 (2016) 067, PRL 118 (2017) 061801, PLB 782 (2018) 510, PRL 123 (2019) 021802, PRL 126 (2021) 071801



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

First Direct Search for the Dyon




CERN Accelerating science

(PRL 126 (2021) 071801)

ABOUT NEWS

News › News › Topic: Physics

Voir en français

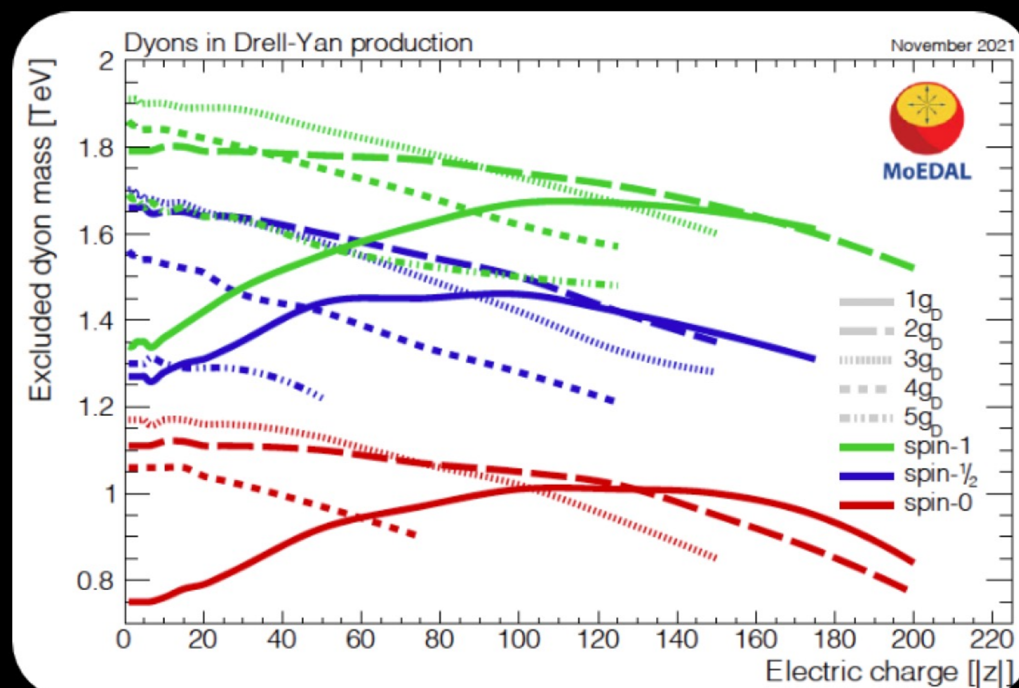
MoEDAL hunts for dyons

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

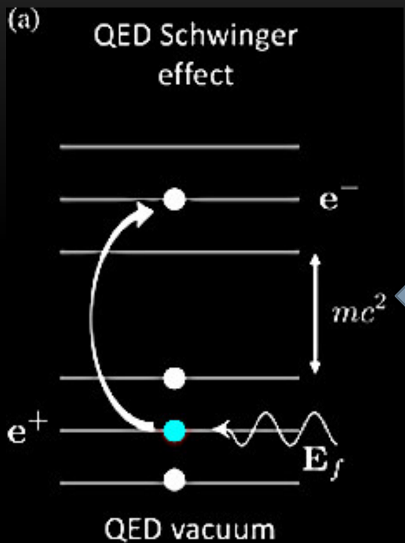
17 FEBRUARY, 2020 | By Ana Lopes

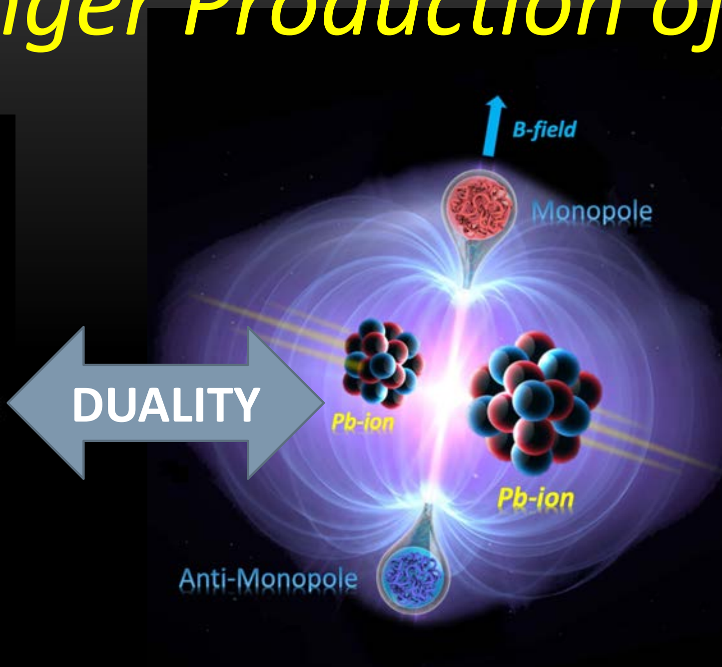
Predicted by Schwinger in 1969 a dyon has electric &magnetic charge

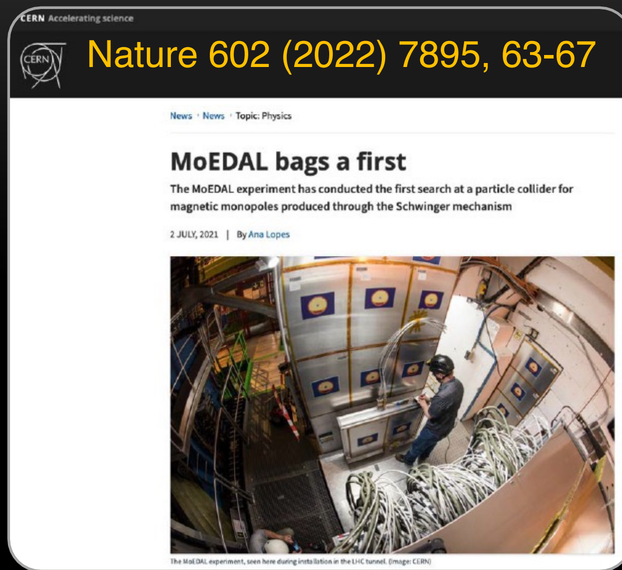
- *Mass limits 750-1910 GeV were set for dyons with ≤5g_D & electric charge ≤ 200e*



Schwinger Production of Monopole Pairs






CERN Accelerating science

Nature 602 (2022) 7895, 63-67

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)

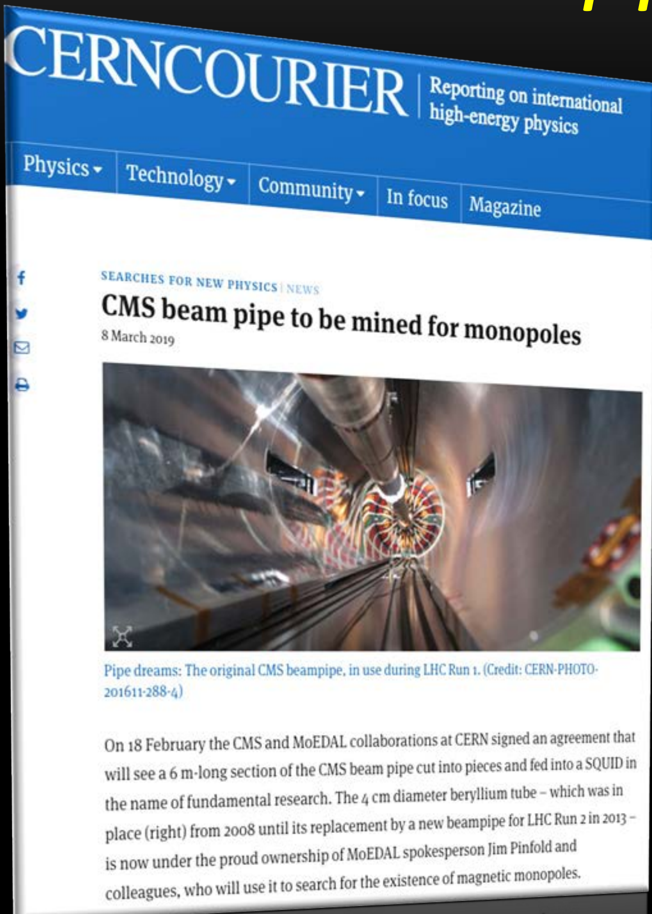
Pair production of electron-positron pairs in a very strong electric field

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


CERNCOURIER | Reporting on international high-energy physics

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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*

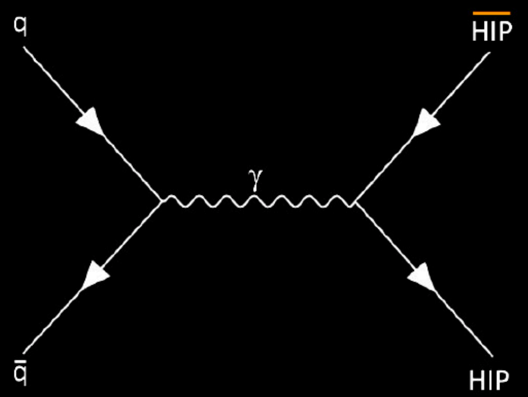
$$\Delta I = \frac{4\pi N}{L} g_D$$

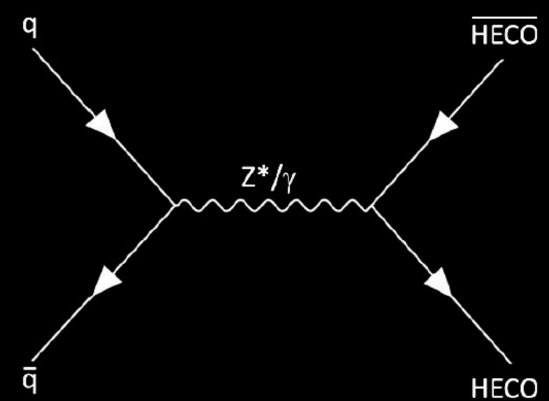
Signal for a monopole is a continuing current in the SQUID after the monopole has passed through

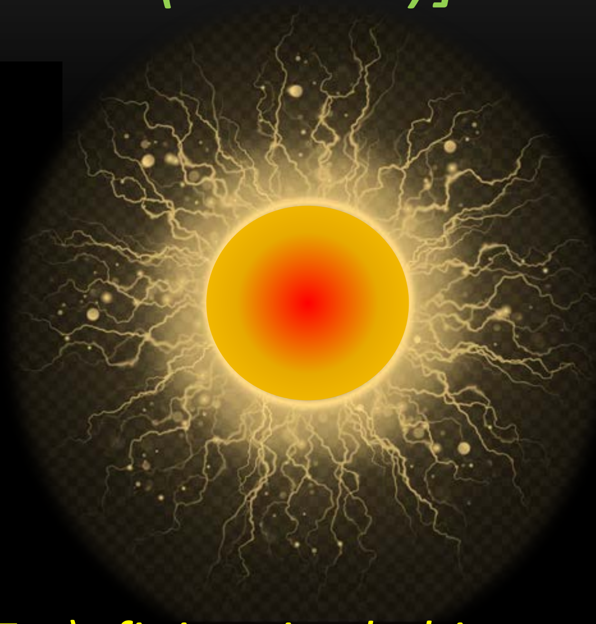
- *Analysis of the beampipe is underway*

Searching for HECOs

[Highly Electrically Charged Objects (HECOs)]



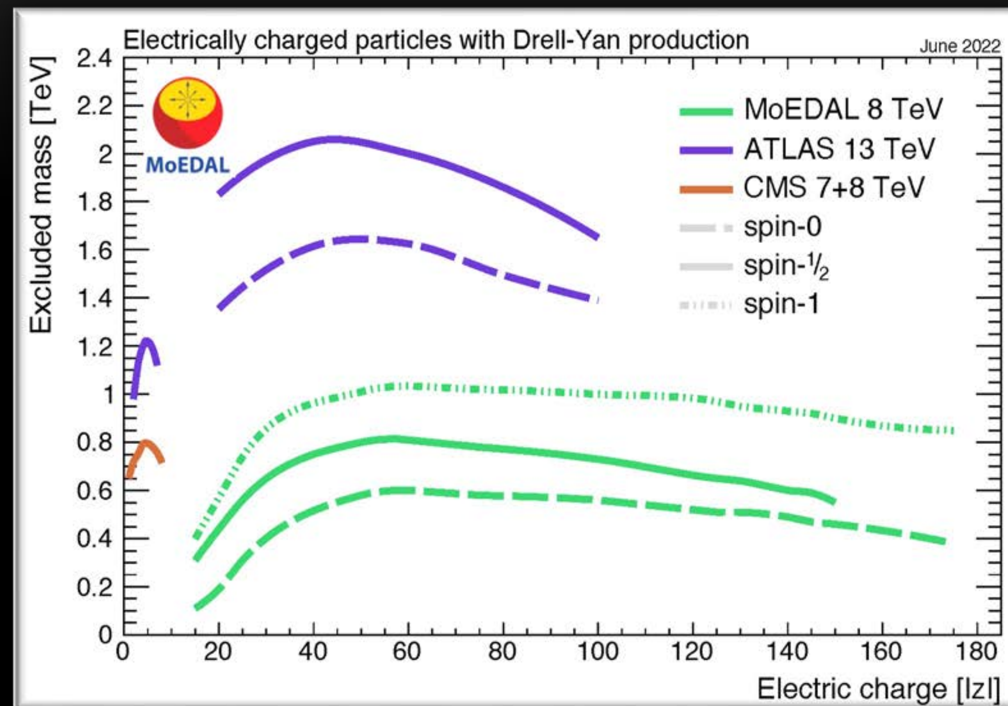




- *Highly Electrically Charged Objects (HECOs, Q > ~5e): finite-sized objects (Q-balls), condensed states (strangelets), microscopic black holes (through their remnants),etc.*
- *Drell-Yan production:*
  - *Z exchange is taken into account for fermions [Song, Taylor, J.Phys.G 49 (2022) 045002]*
  - *Non-perturbativity 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]

Phase 1 - the MoEDAL Detector at Run-3 [2022- ?]

The Search Highly ionizing particles (HIPs continue) with:

5 x Higher Instantaneous Luminosity at IP8

a) Improved Detector Efficiency
b) X10 lower threshold

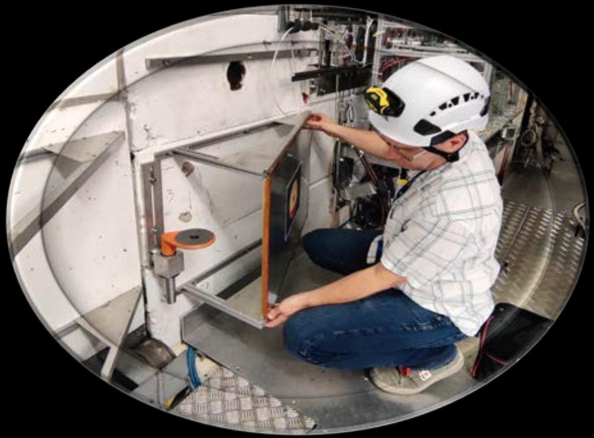
Slightly higher Centre-of-mass Energy

Upgraded MoEDAL Installed for Run-3

MAPP
MoEDAL

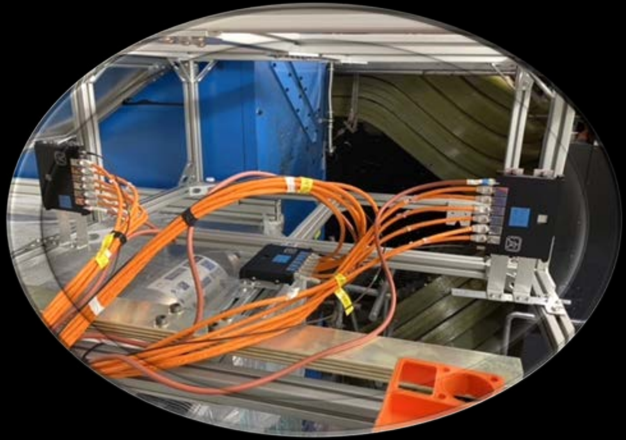
Upgrades to the Run-2 MoEDAL Detector, for Run-3 – completed in March 2023

VELO-TOP NTD array installed



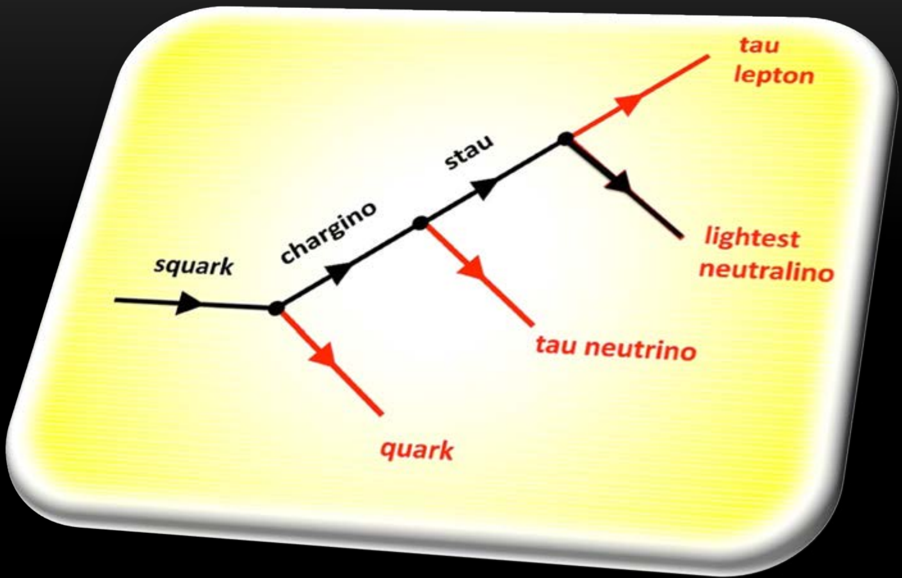
NTD Stacks Point to IP

Forward MMT box reconfigured



TimePix3 Chips connected to LHC clock

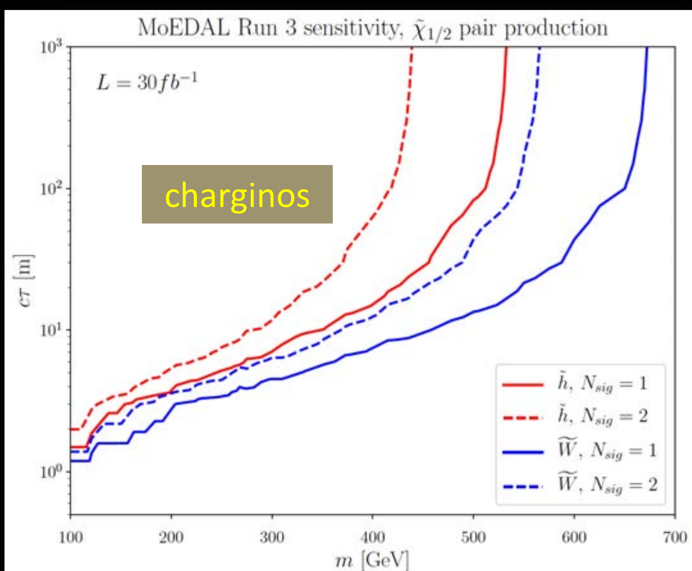
Detecting Long-lived SUSY Partners (1)



- *SUSY charged LLP states:* ***sleptons, R-hadrons, charginos***
  - *plus* ***doubly charged higgsinos*** *in L-R symmetric models*
- *ATLAS & CMS have constrained these spartners. Analyses limited by:*
  - *Trigger requirements*
  - *Offline selections to suppress SM backgrounds*
  - *Timing: signal from slow-moving particles to arrive in correct bunch crossings*
- *Due to absence of* ***trigger, timing & SM backgrounds****, MoEDAL can relax selection requirements + increase sensitivity to charged, SUSY LLPs*

Long-Lived SUSY Particles in MoEDAL (2)

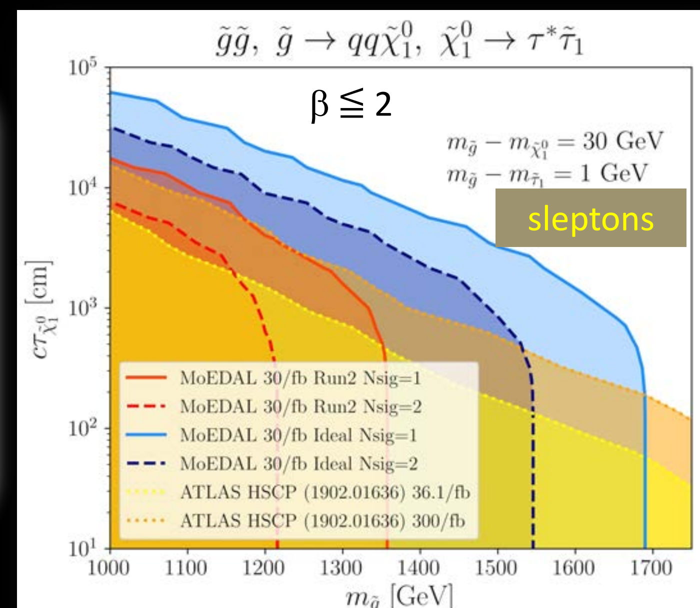
- *Benchmark decay chain: $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \tau^{\pm}\tilde{\tau}_1$*
  - *$\tilde{\chi}_1^0$ moderately long-lived ➜ decays in tracker*
  - *$\tilde{\tau}_1$ charged long-lived ➜ interacts with detector*
- *Other decay chains studied: $\tilde{g} \rightarrow jj\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \rightarrow \nu_\tau\tilde{\tau}_1$, etc.*



p-p $\rightarrow$ YY + X, Y is a R-hadron containing
The strongly interacting gluino, squark, stop,
Chargino ($c^{\pm}$), or charged slepton ($\ell^{\pm}$), etc.

EPJC 80 (2020) 572

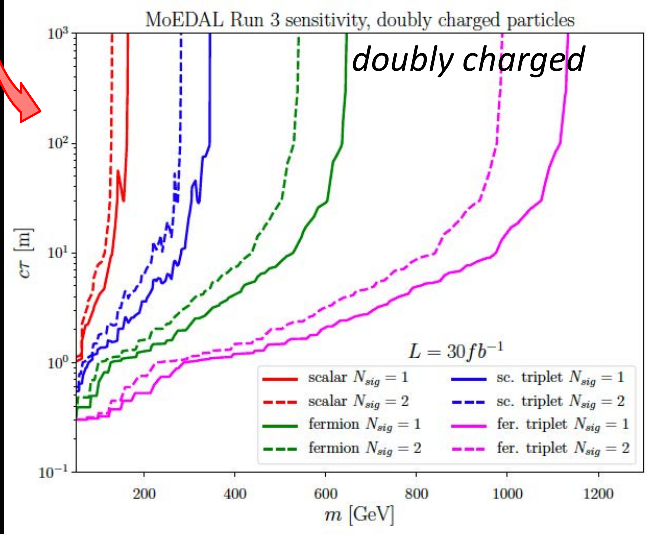
MoEDAL can cover long-lifetime region in Run 3 for gluinos, stops, sleptons and charginos



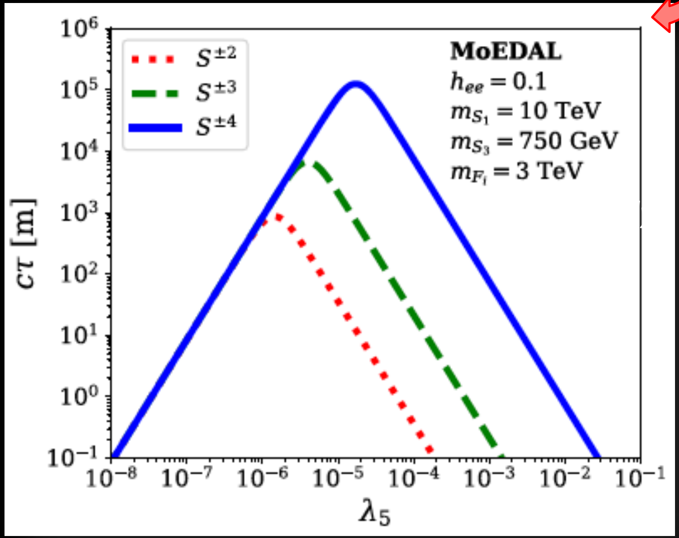
Eur.Phys.J.C 80 (2020) 5, 431 e-Print: 2001.05980 [hep-ph]

Multiply Charged Particles – Specific Models

- *Doubly charged particles*
  - *Predicted in left-right symmetric models, seesaw neutrino models, little Higgs models, … (+ SUSY extensions), extra dimensions, …*
  - *Models considered: (scalar, fermion) × (SU(2): singlet, triplet)*
- *2-, 3-, 4-ply charged states occur in a class of neutrino mass models*
  - *long-lived due to small neutrino mass and high electric charge*



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



Authors added doubly charged scalars & fermions in various SU(2)L rep's, to the SM particle content .

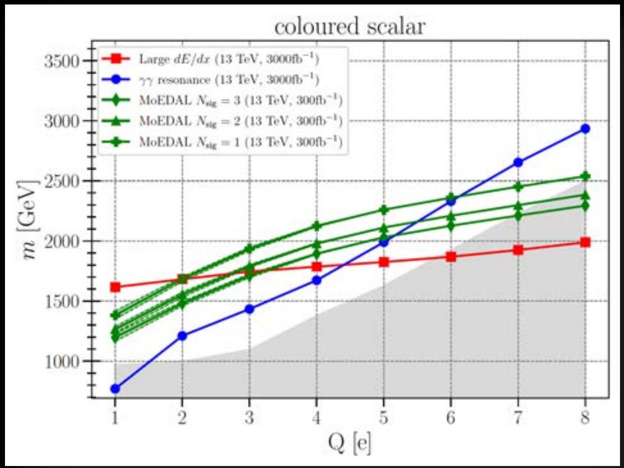
Acharya *et al*, EPJC 80 (2020) 572

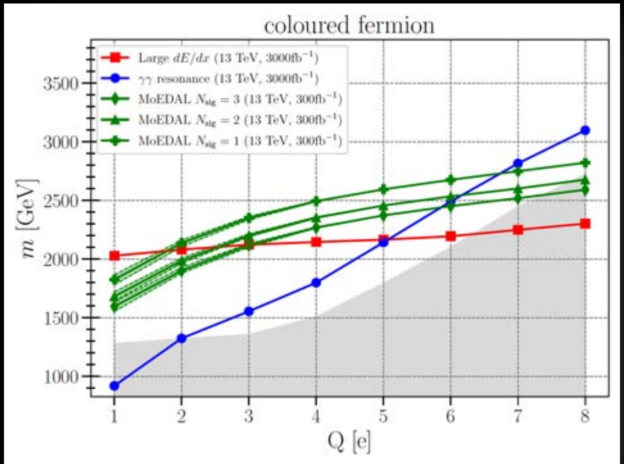
The λ_5 term breaks the lepton number symmetry and Is needed for neutrino mass generation

Hirsch *et al*, EPJC 81 (2021) 697

Multiply Charged Particles – Generic Case

- *Phenomenological study independent of underlying model*
- *Includes all production processes, including those with photons*
  - *Most experimental searches only assume Drell-Yan*
  - *For high charges, photon contributions become very relevant*





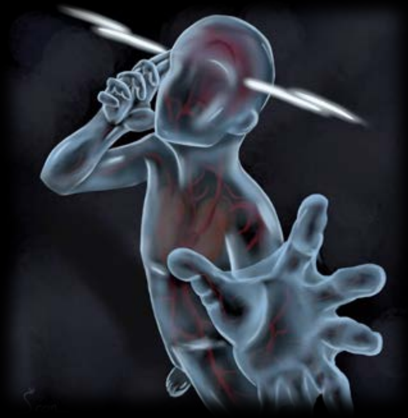
Altakach, Lamba, Masełek, VAM, Sakurai, 2204.03667 [hep-ph]

- *Grey region excluded by ATLAS/CMS Run 1 / Run 2 searches*
  - *ATLAS/CMS direct detection based on searches for large dE/dx better sensitivity at low charges*
- ***MoEDAL has best sensitivity at intermediate electric charges at HL-LHC***

Phase 1 - The MAPP-1 Project for Run-3

The Search for (HIPs)

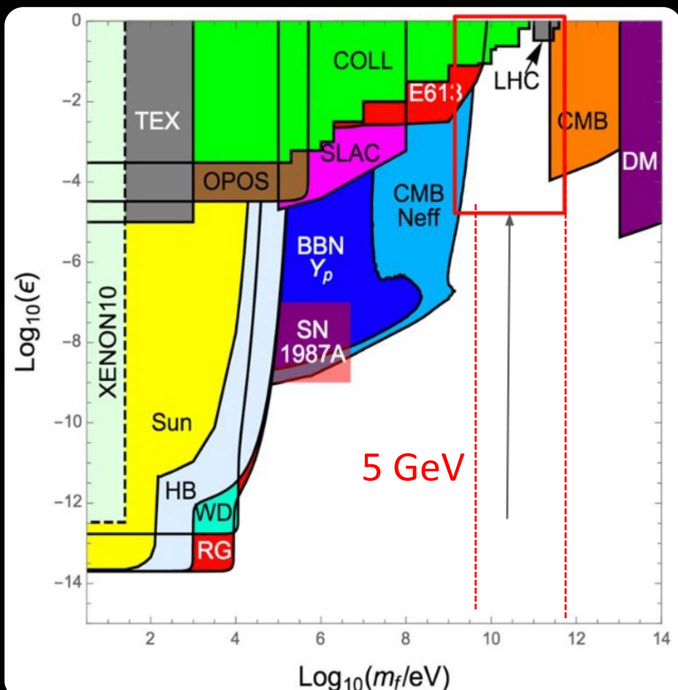
The Search for LLPs



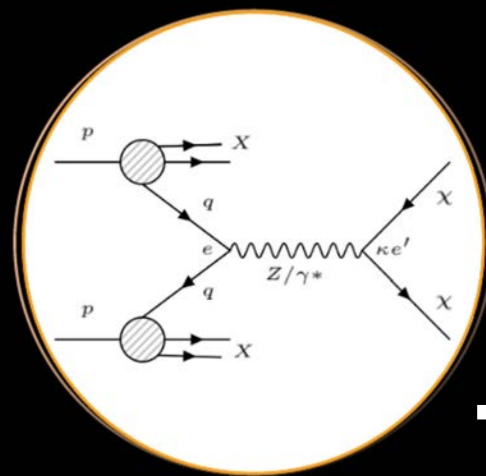
The Search for Feebly Interacting Particles (FIPs)

Production of Milli-charged at Colliders

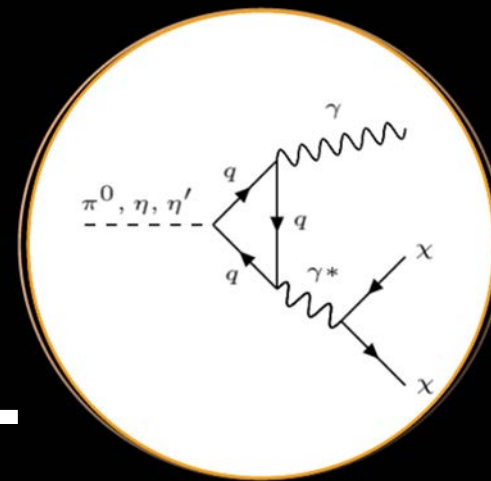
mCPs arise naturally from the dark sector eg via the Vector Portal/Dark Photon



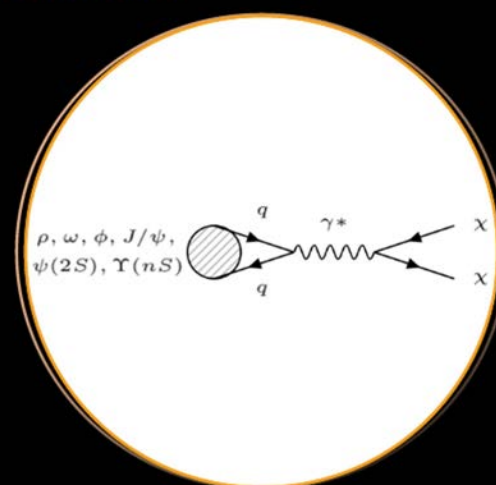
The Sweet Spot
arXiv:1511.01122



via the **Drell-Yan Process**

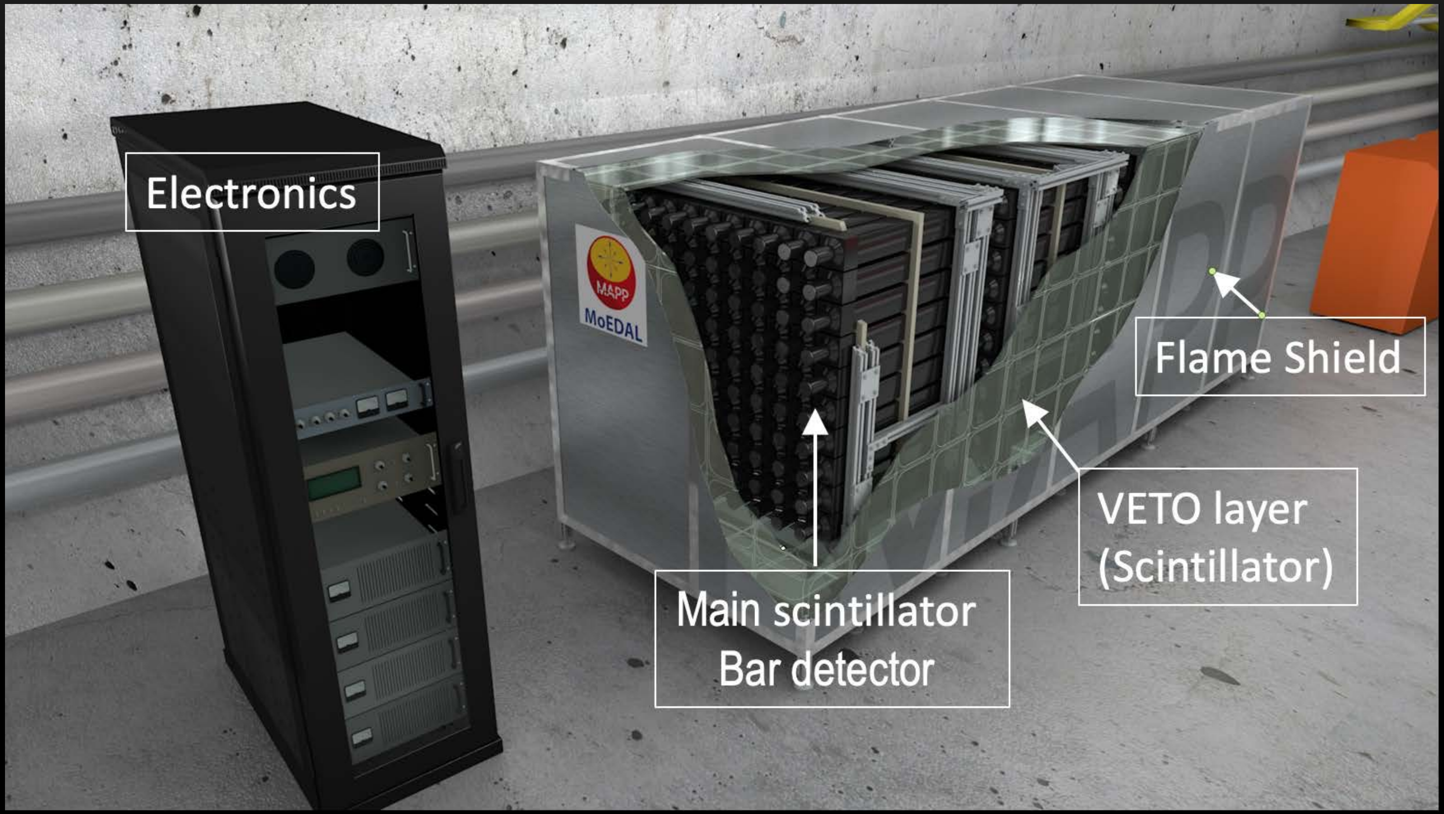


via **Dalitz decays of pseudoscalar mesons**



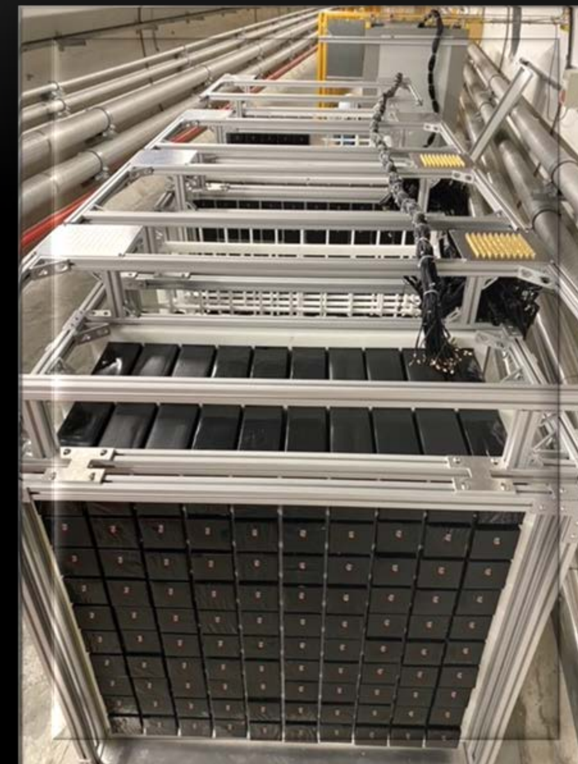
via **direct decays of vector mesons**

The MAPP-1 Detector at UA83



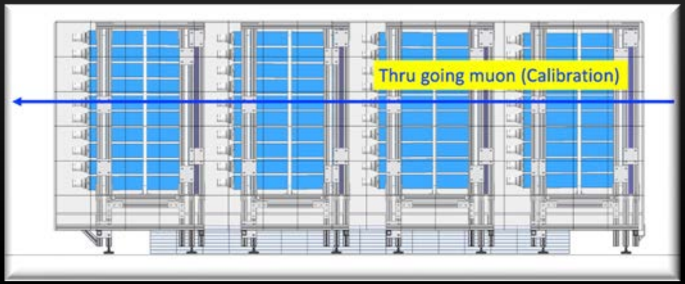
- *400 scintillator bars (10 x 10 x 75 cm^3) in 4 sections readout by PMTs - Protected by a hermetic VETO counter system*
- *Each through-going particle sees 3m of scintillator readout by a coincidence of 4 low noise PMTs*

MAPP-1 is Currently Being Installed

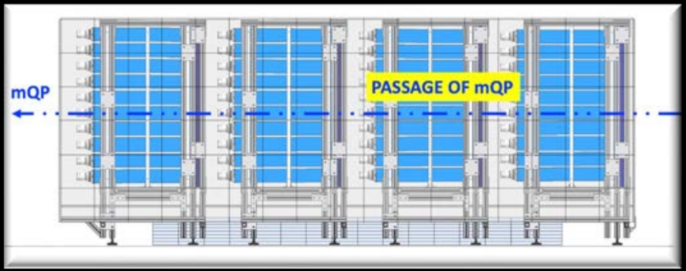


- *Installation proceeds when access to UA83 is permitted, the above photographs were taken in March 2023*
- *The next installation period will be in the TS in June 2023*
- *We expect to start taking data in July 2023.*

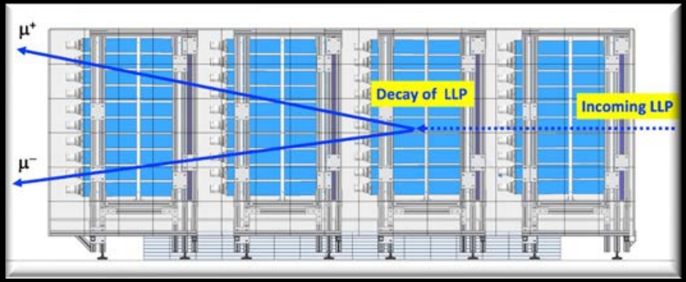
MAPP – Modes of Detection



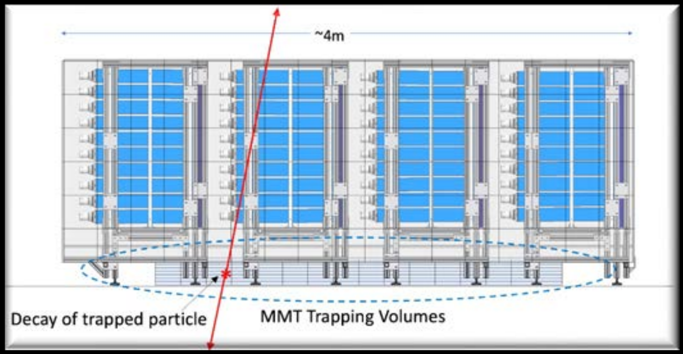
Muons from IP (Calibration)



Millicharged particle detection

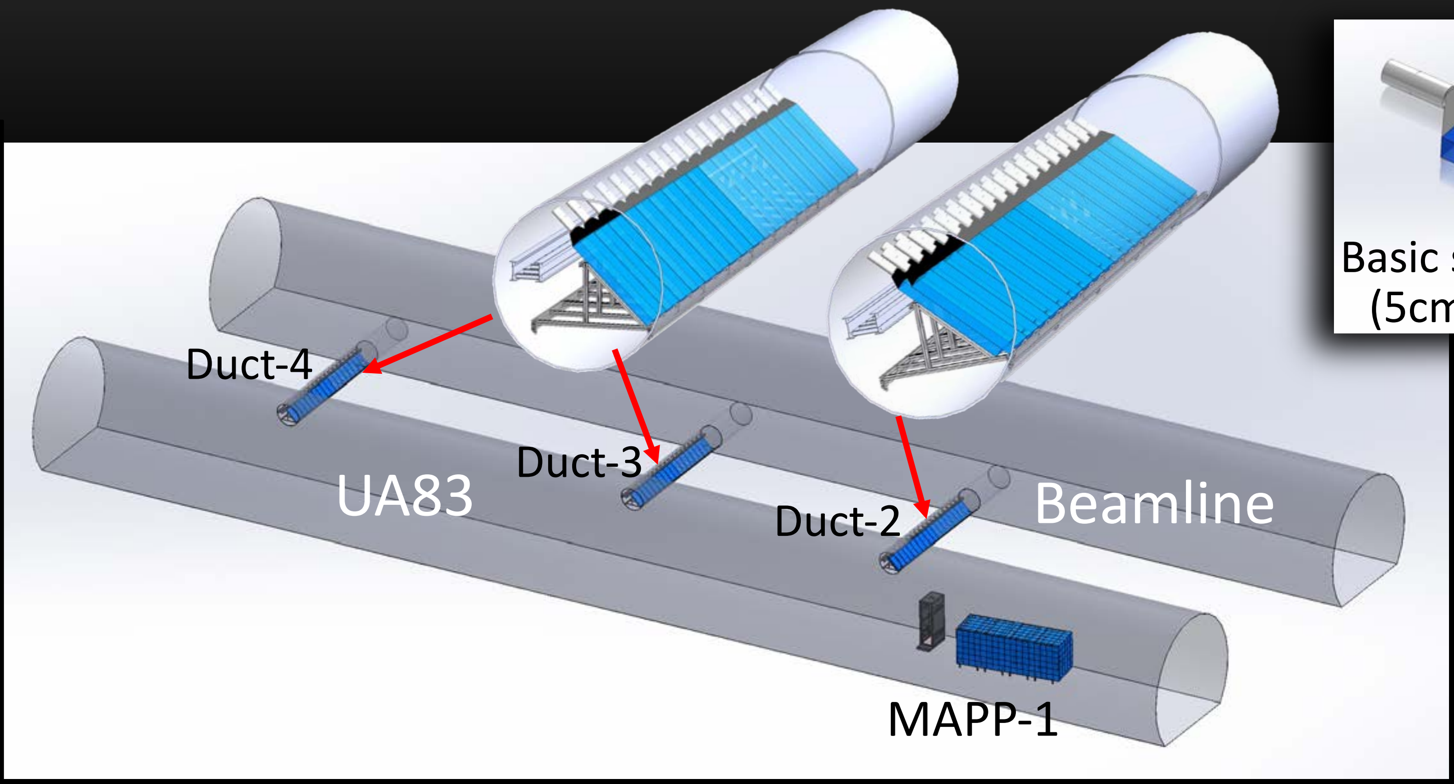


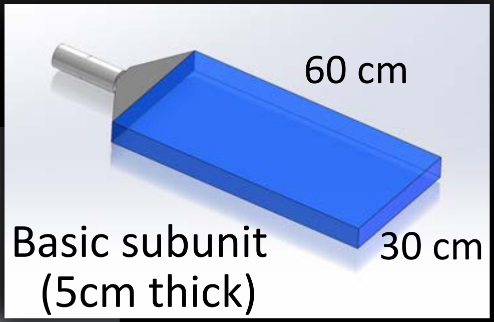
Neutral LLP Detection



Charged LLP Detection
(In conjunction with MoEDAL)

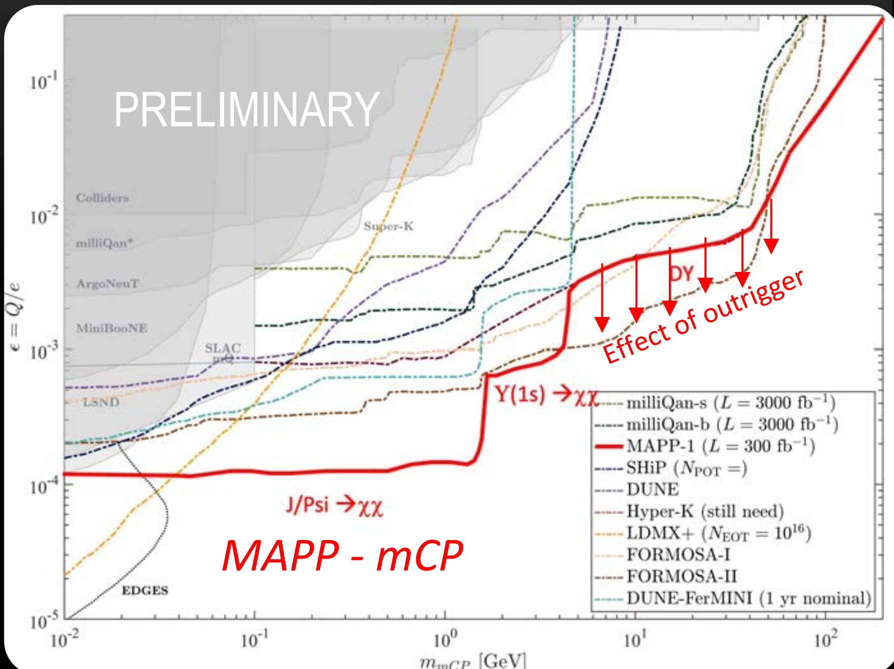
The MAPP-1 Outrigger Detector

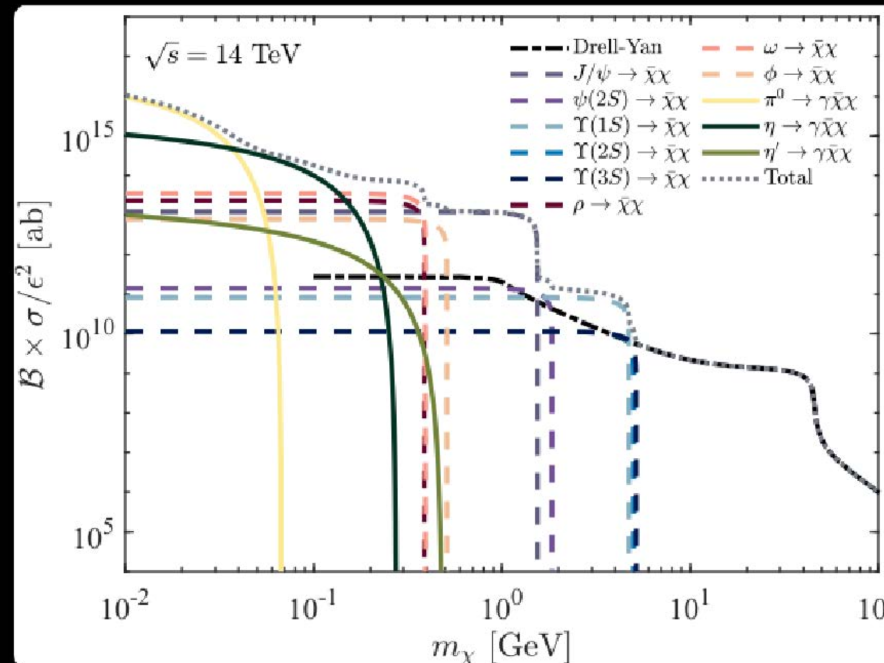




- *The outrigger's purpose is to increase the acceptance of MAPP-1 at higher mass & larger fractional charge*
- *Size of the scintillator "planks" 6m x 0.6m x 5 cm, inclined at 45 deg.*
- *Covers from ~1.7 deg. to 5.3 deg.*

The MAPP-mQP Bar Detector Sensitivity





mCP Prod. X-secs for 14 TeV pp Collisions

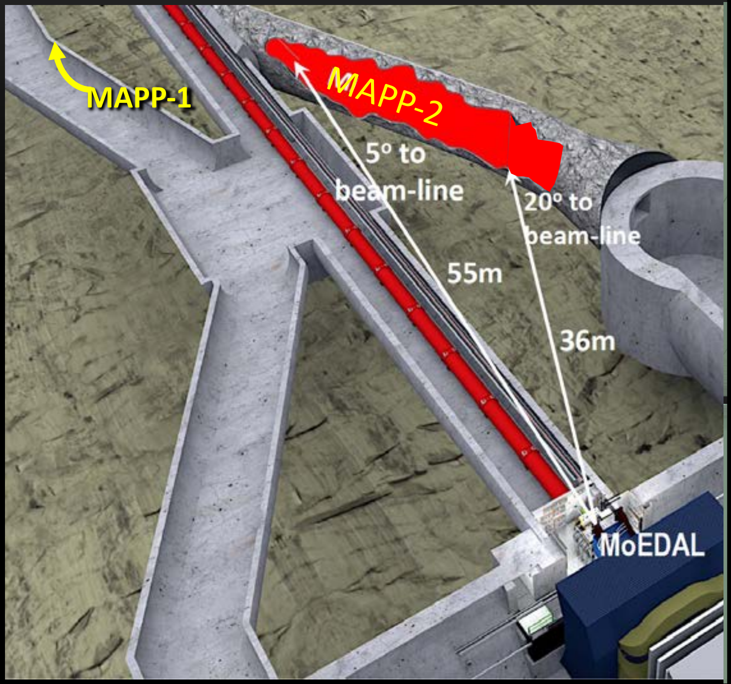
- *LEFT: Estimated reach of MAPP-mCP at √ s = 14 TeV for HL-LHC*
  - *We are planning an outrigger detector to enhance the DY sensitivity*
- *RIGHT: the addition of the resonances and meson decays to mCPs enhances the number of lower mass mCPs*
- *CAVEAT: At present the MAPP-mQP plots assumes 100% detector eff.*

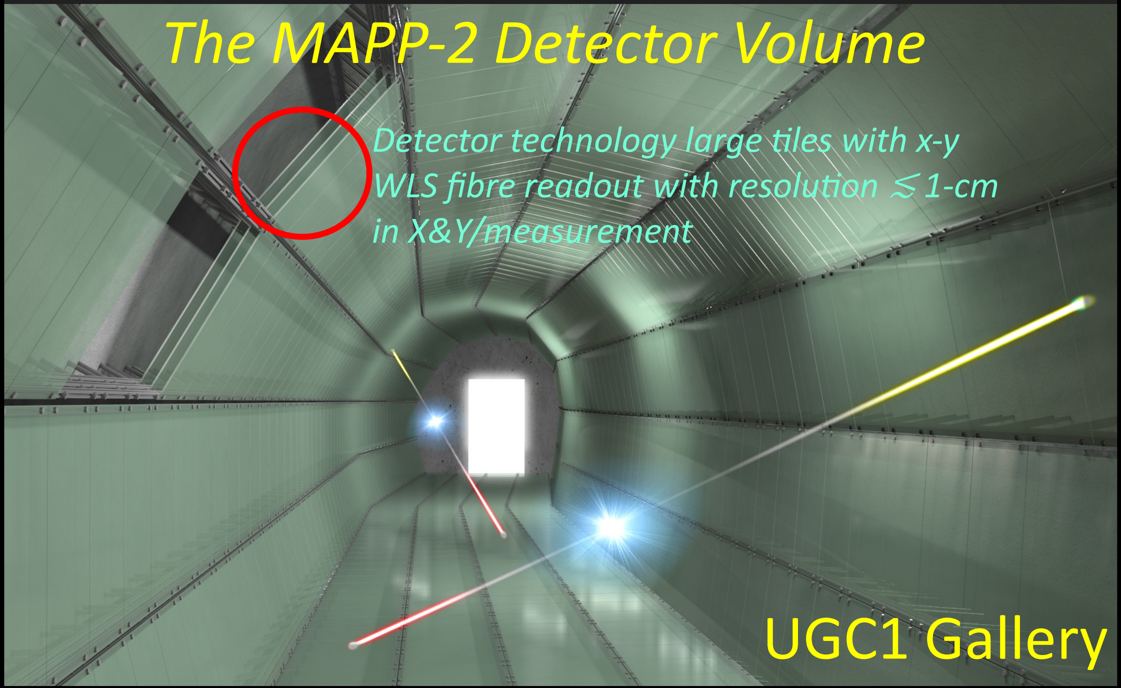
MAPP
MoEDAL

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





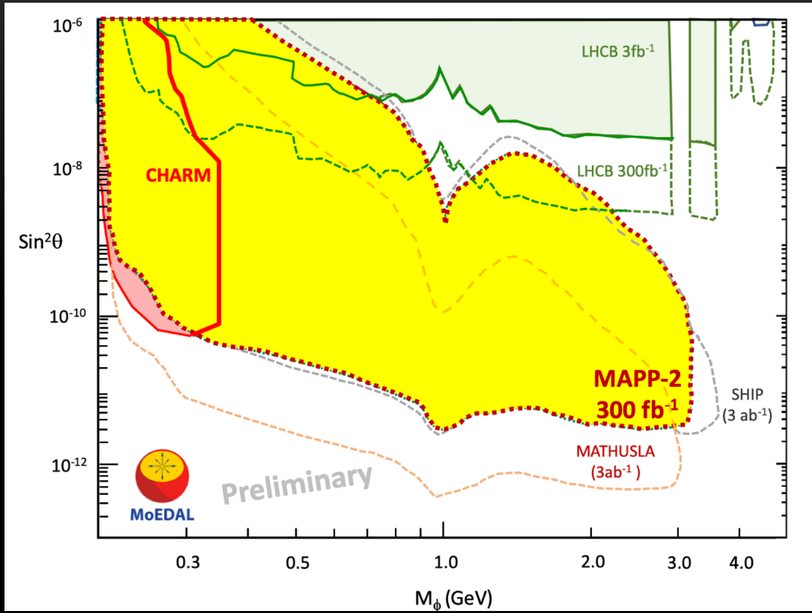
- *The MAPP-2 detector would fill the UGC1 gallery adjacent to LHCb*
  - *The UGC1 gallery would be prepared during LS3 prior to HL-LHC*
  - *The tracking detectors would form 3 or 4 hermetic containers - one within the other – lining the walls of UGC1*

- *MAPP-2 ~1200 m^3 of instrumented decay volume. Estimated technical*
- *Costs of MAPP-2 ~$3-4 M including 0.5K of civil engineering.*

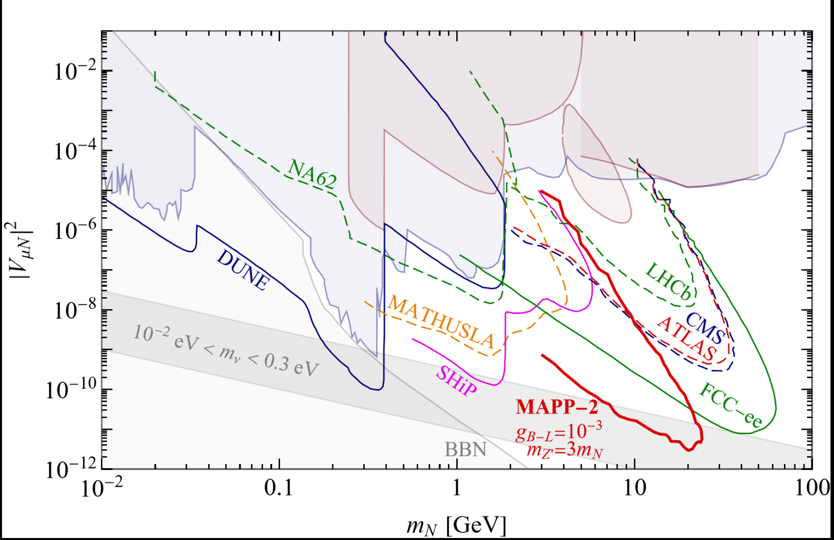
MAPP-2: Example Physics Studies

- *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*
- *Complementary coverage for LHCb & MATHUSLA*

V_{mN}^2 is the active-sterile neutrino mixing strength



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



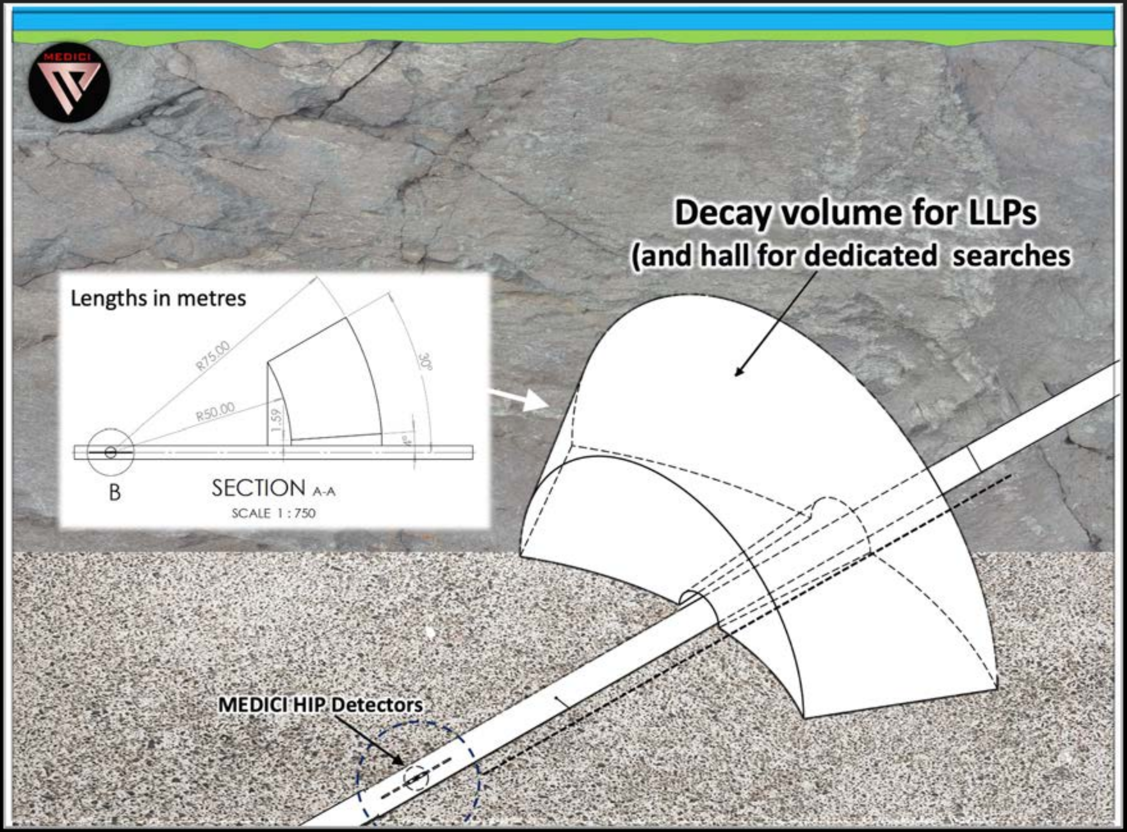
To be published in EPJ-ST

The MEDICI* Facility for the 100 TeV FCC

MoEDAL-MAPP Type Facility for the FCC.
A quick look at some physics channels

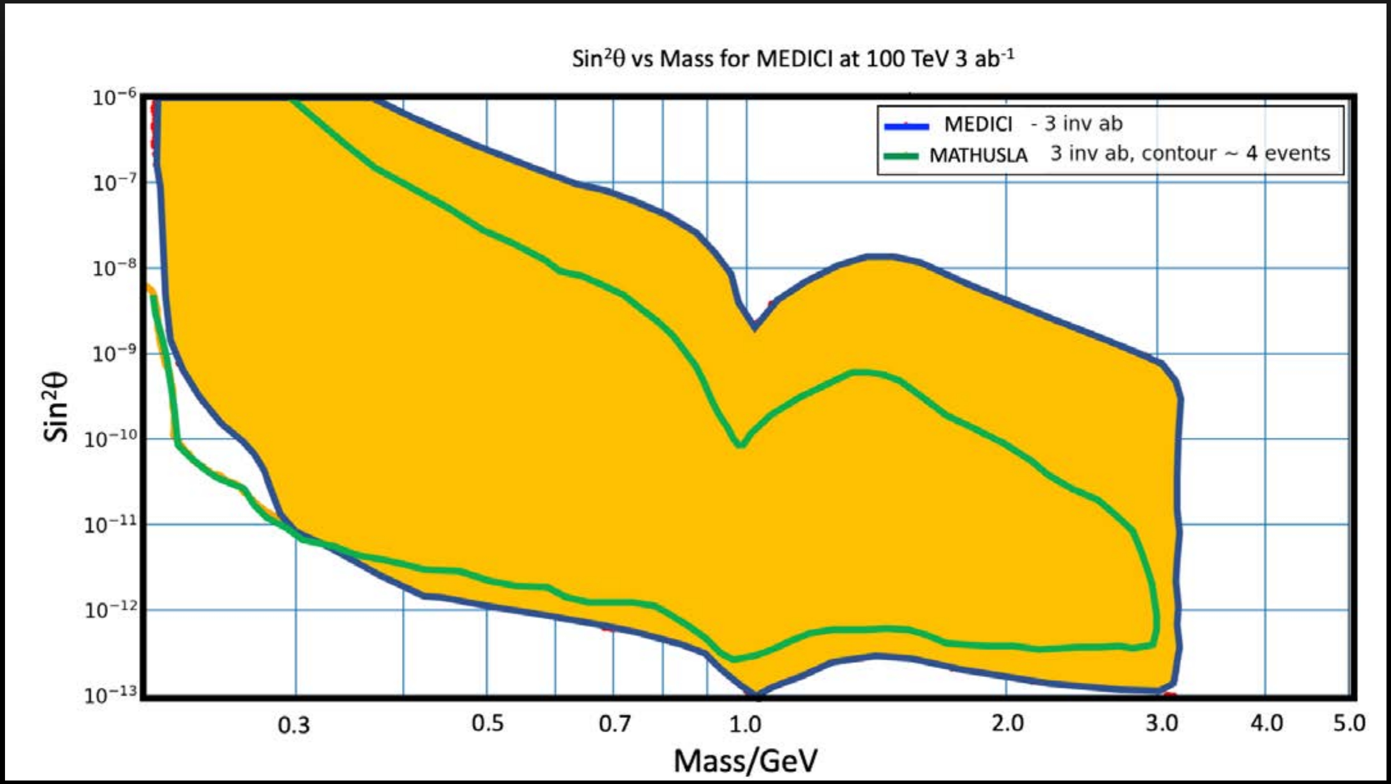
* MEDICI (Monopole and Exotics Detector Infrastructure for Colliding Ions)

A Prototype MEDICI Facility



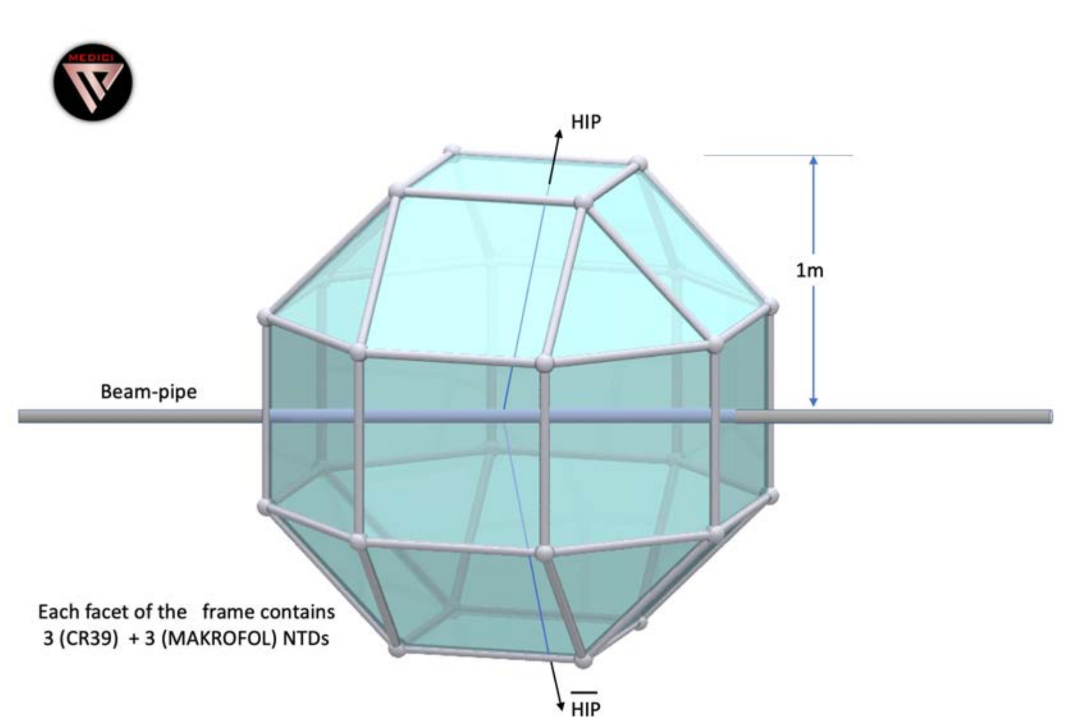
- *The hall acts as a monitored decay volume similar in principle to MAPP-2 and as an experimental area for deployment of various dedicated detectors protected by some 50m of rock from the IP & 100m of rock from CRs*
  - *The IP region could be used for a HIP detectors such as MoEDAL*
  - *Other detectors for FIPs and LLPs etc can be deployed in the hall*

MEDICI's Search for LLPs – an Example



- *Example benchmark process used also for MAPP-2 – a dark sector scalar.*
- *MEDICI is highly competitive with and more cost effective (\$15 -\$20M) then MATHUSLA (\$100M - \$200M)*
    - *Protected from CR background by ~100m Rock overburden*

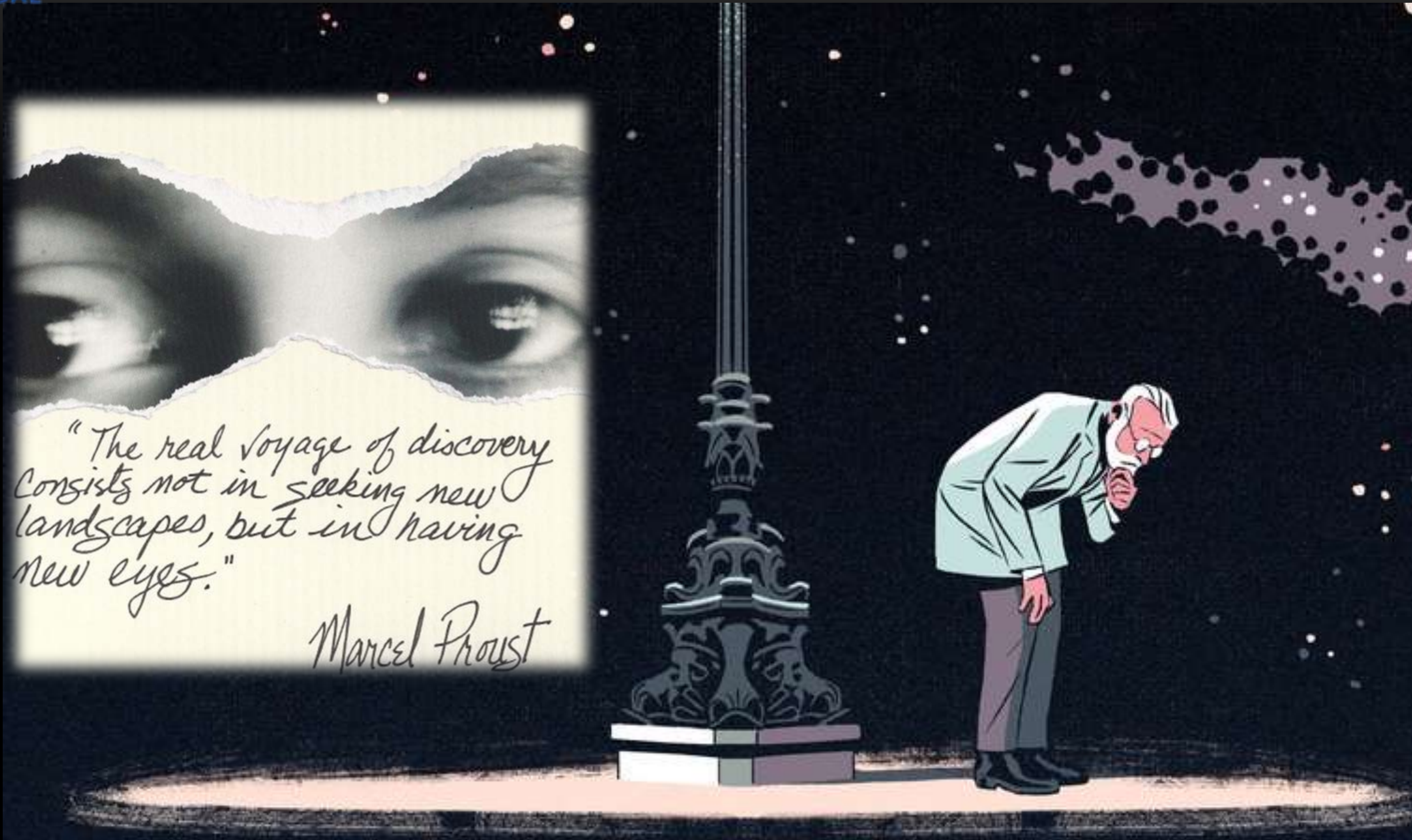
Searching for HIPs at the 100 TeV FCC



MoEDAL at the FCC – a PLASTIC (CR39) BALL

- *The FCC version of MoEDAL would be a Plastic Ball detector of NTD detectors deployed directly around the Interaction Point.*
  - *A dedicated IP for MEDICI would allow easy change of plastic to avoid radiation damage problems.*
  - *Initial physics studies have shown that an NTD "PLASTIC Ball" detector could quest for monopoles as massive as 20-30 TeV/c^2 with 3 ab^{-1}.*

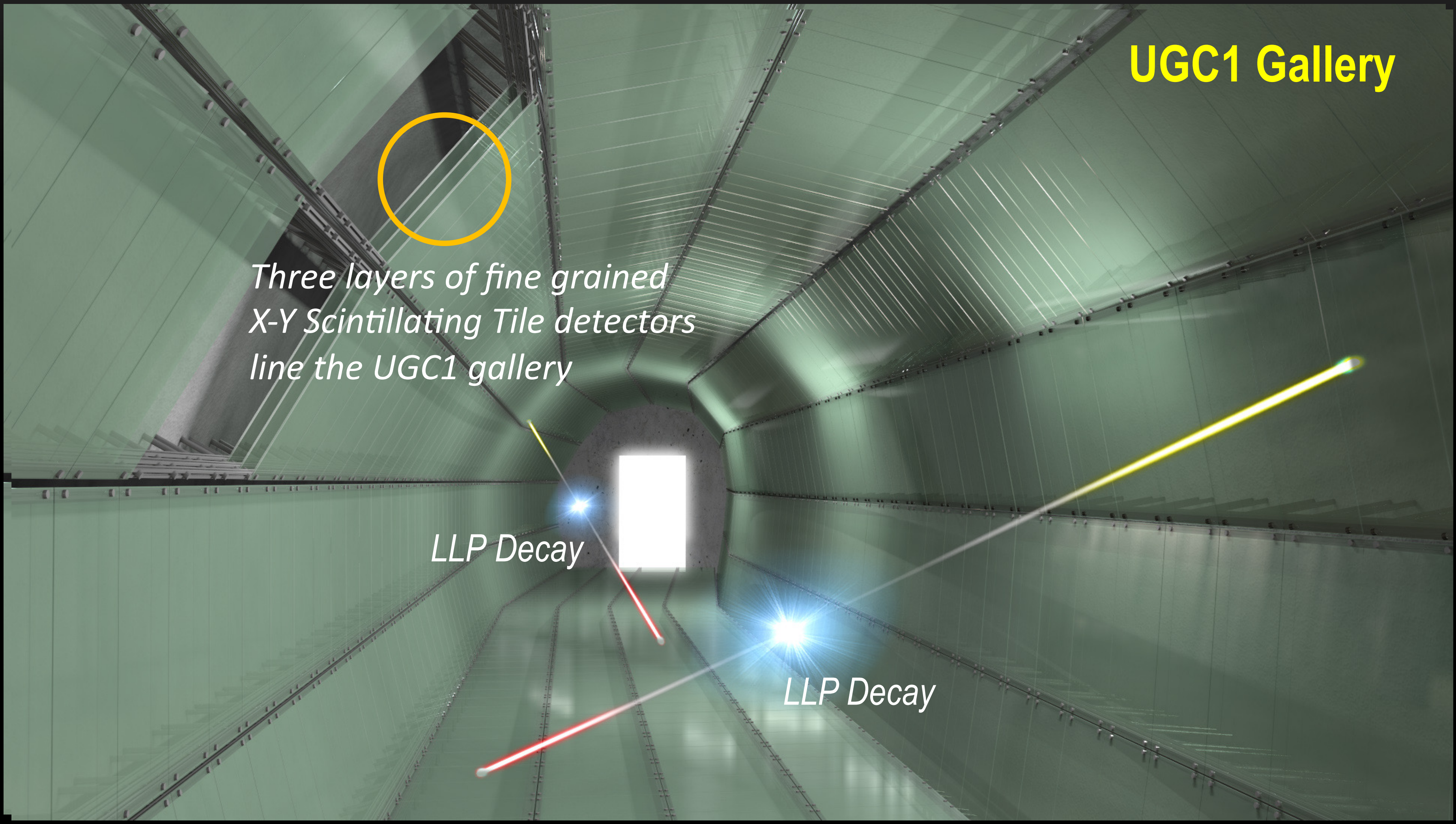
Concluding Remarks



With dedicated detectors as our new eyes we hope to reveal physics beyond the SM illumination at the LHC and the FCC

EXTRA SLIDES

The MAPP-2 Detector Volume

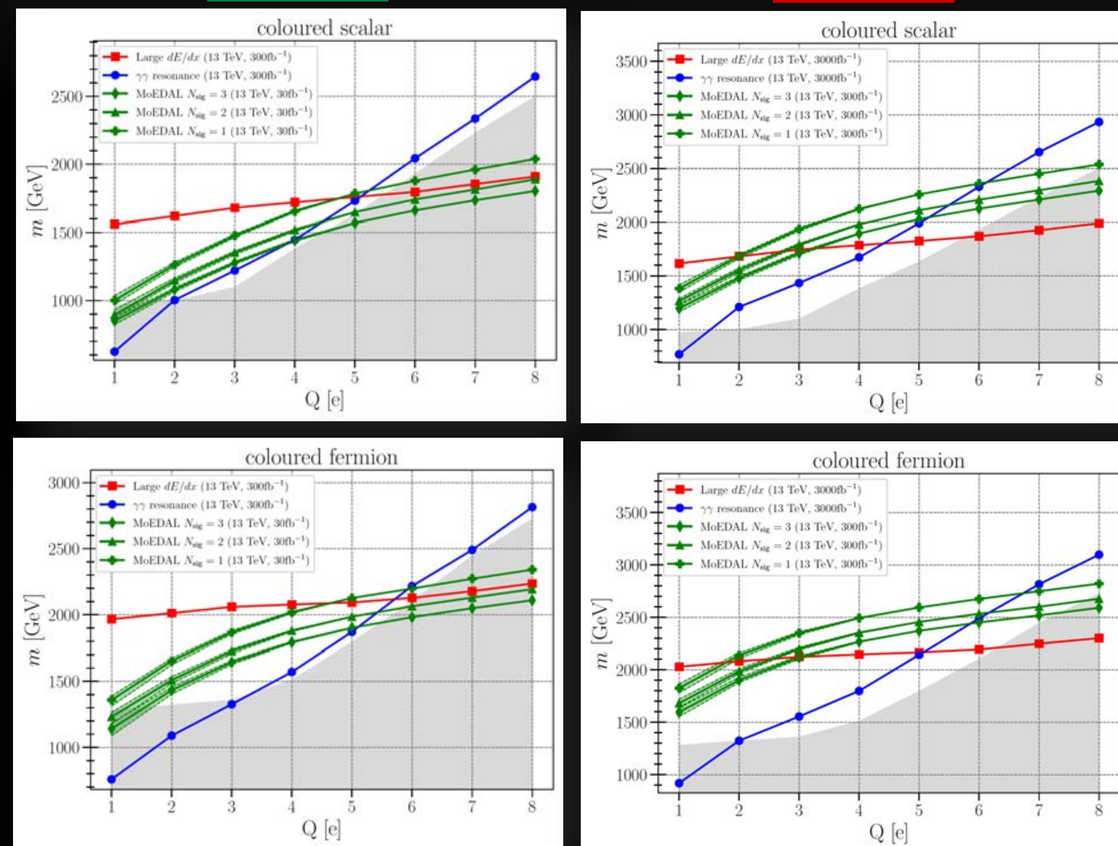


MAPP-2 ~1200 m^3 of instrumented decay volume. Estimated technical costs of MAPP-2 ~$3-4 M including 0.5K of civil engineering.

MOEDAL VS. ATLAS/CMS

- *Grey region excluded by ATLAS/CMS Run 1 / Run 2 searches*
- *ATLAS/CMS direct detection based on searches for large dE/dx ⟶ better sensitivity at low charges*
- *ATLAS/CMS searches for diphoton resonances offer better coverage at high charges*
- ***MoEDAL has the best sensitivity at intermediate electric charges at HL-LHC***

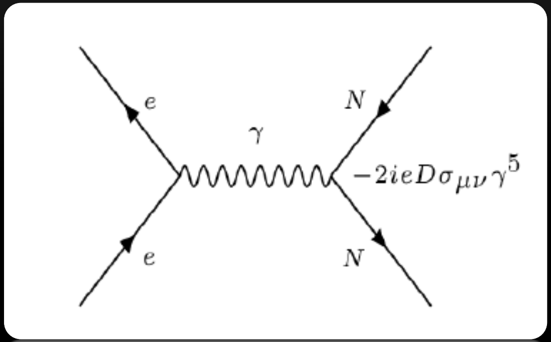
Run 3 | HL-LHC

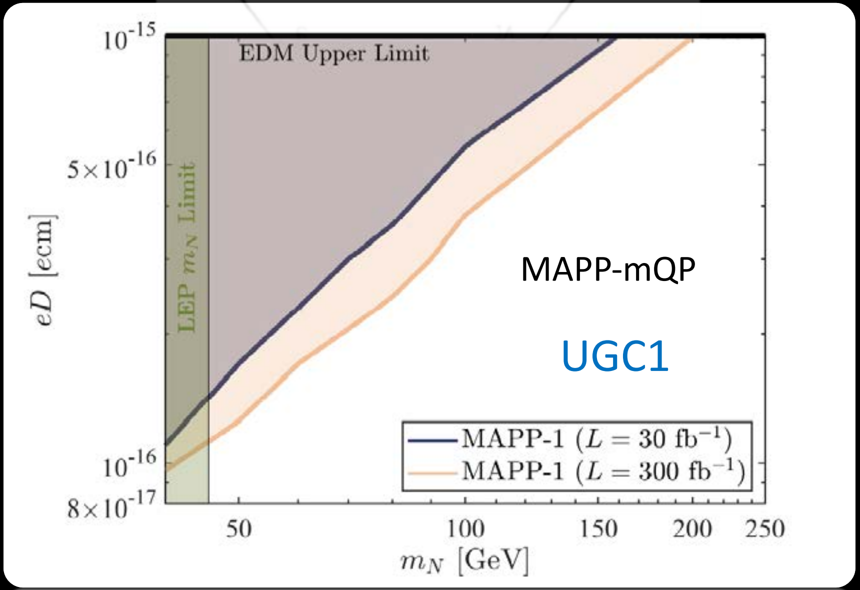


Altakach, Lamba, Masełek, VAM, Sakurai, 2204.03667 [hep-ph]

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)

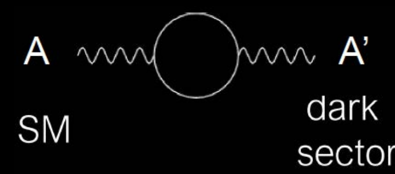
Searching for Charged FIPs at the LHC

- *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'*

$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \underbrace{i\bar{\psi}'(\gamma^\mu\partial_\mu + ie'\gamma^\mu A'_\mu + iM_{\text{mCP}})\psi'}_{\text{“dark fermion” with mass } M_{mCP}\text{, charge } e'} - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

massless "dark photon"

mixing term



$\kappa \sim 10^{-3} - 10^{-2}$

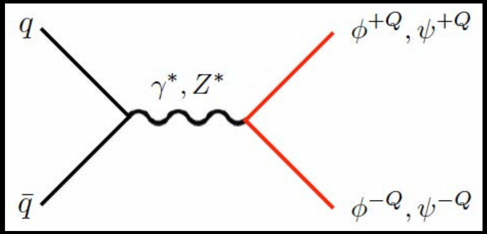
(naturally $\sim \alpha/\pi$)

- *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*

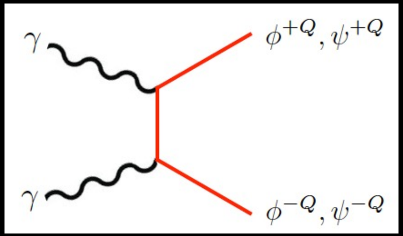
Multiply Charged Particles – Generic Case

- *Phenomenological study independent of underlying model*
- *Includes all production processes, including those with photons*
  - *Most experimental searches only assume Drell-Yan*
  - *For high charges, photon contributions become very relevant*
  - *Production of Bound State $\gamma\gamma \rightarrow \gamma\gamma$ detectable by ATLAS/CMS but not MoEDAL*

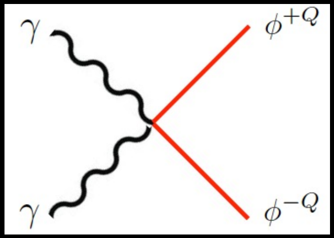
SU(2) singlet	color singlet	color triplet
spin 0	colorless scalar	colored scalar
spin 1/2	colorless fermion	colored fermion



s-channel (Drell-Yan)



t-channel γγ fusion



seagull γγ fusion (scalar only)

Altakach, Lamba, Masełek, VAM, Sakurai, 2204.03667 [hep-ph]