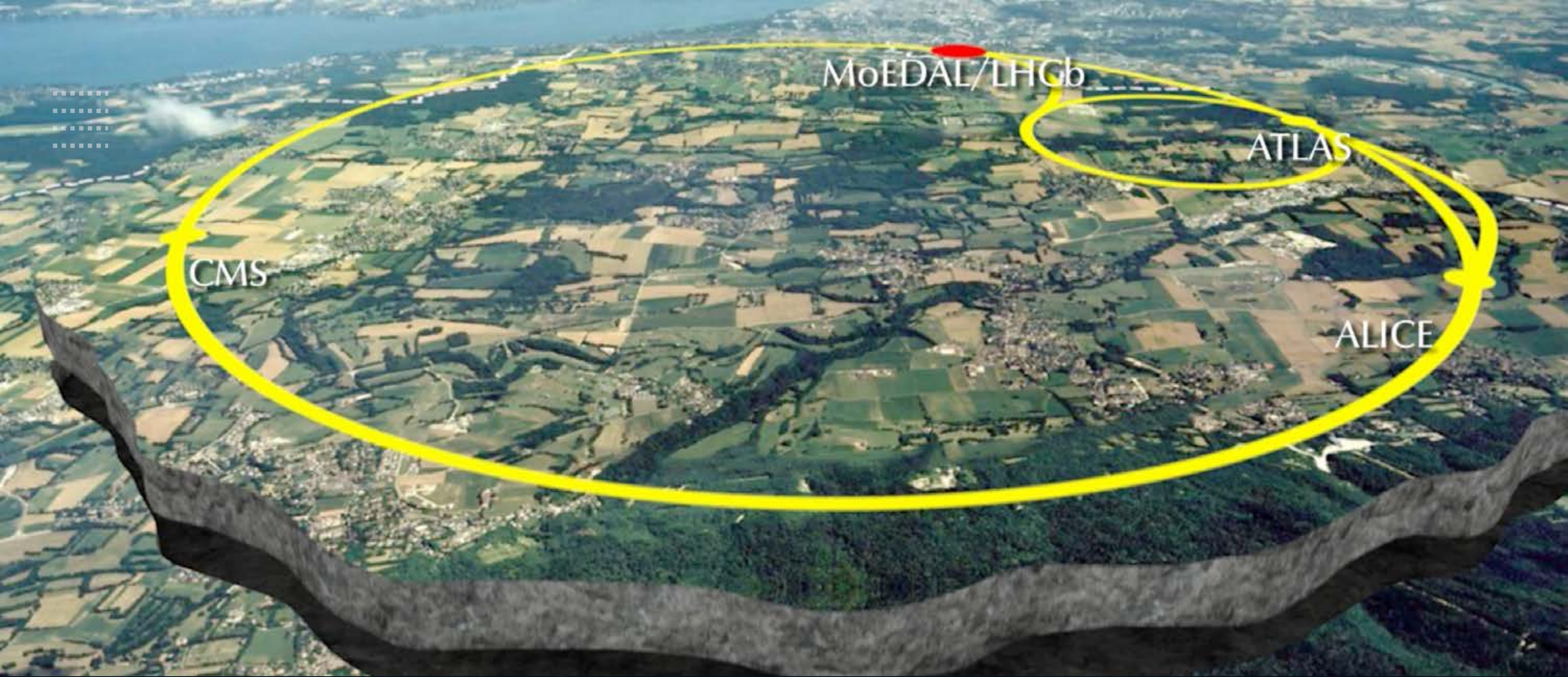


The MoEDAL-MAPP Experiment at the LHC's Run-3 and Beyond

CAP Congress 2023 in Fredericton.

James L. Pinfold for the MoEDAL-MAPP Collaboration

MoEDAL-MAPP 26 Institutes

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

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 Tech. University (IEAP)
University of Helsinki
Institute of Space Sciences Romania
University of Valencia (IFIC)
Vaasa Universities
University of Warsaw (Assoc.)

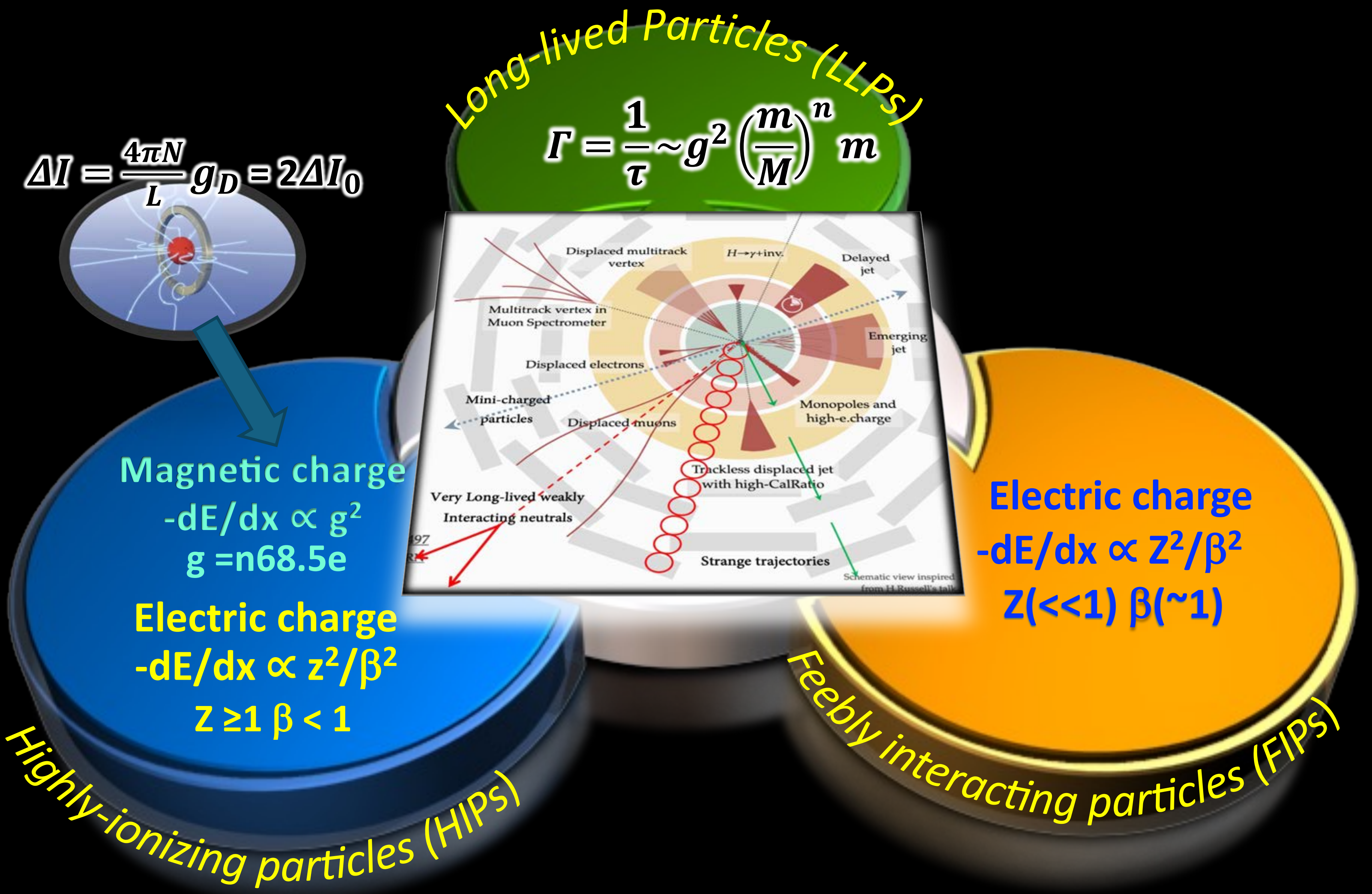
INDIA
University of Calcutta
National Institute of Technology, Kuruksetra IAssoc.)

KOREA
Centre for Quantum Spacetime, Seoul

70 Physicists & Engineers

MoEDAL-MAPP Search for New Physics..

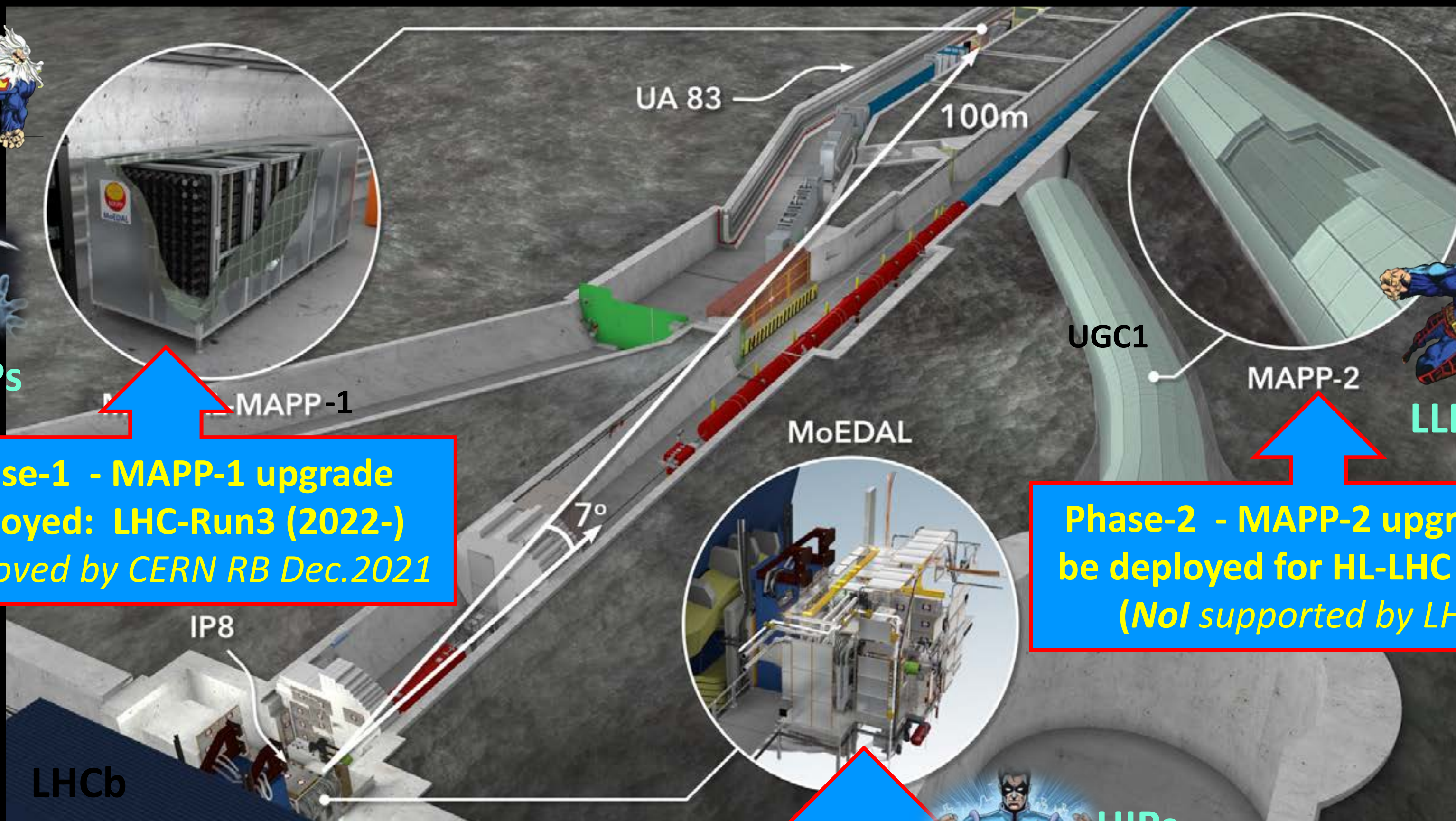
………for which ATLAS & CMS are not optimized



MoEDAL-MAPP a > 25 Year Project

LLPs

FIPs



LLPs

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

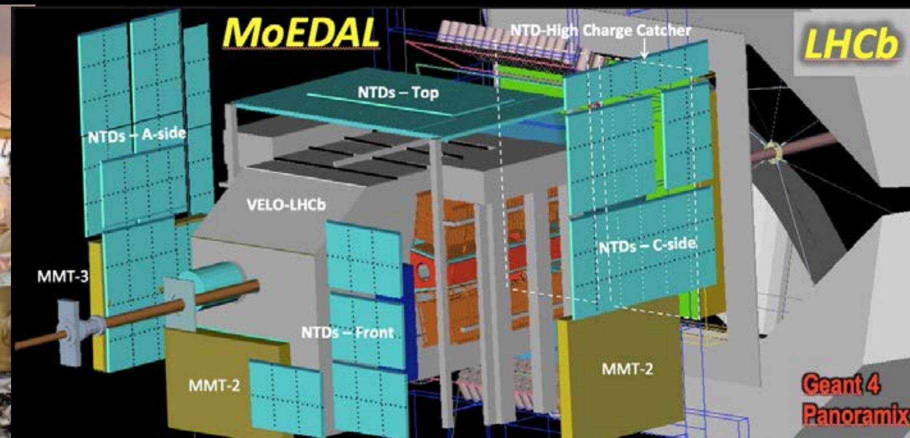
Phase-2 - MAPP-2 upgrade to be deployed for HL-LHC (2027-)
(***NoI** supported by LHCC)*

HIPs

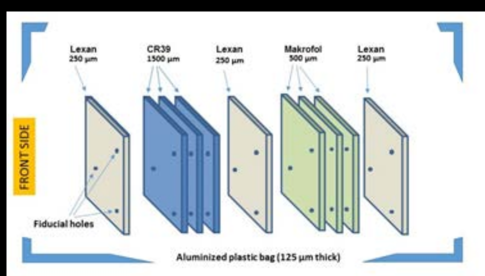
Phase-0 - MoEDAL Detector deployed for LHC-Run-1& 2 (2010 - 18) and Phase-1 - Run-3 (2022 -)
(Approved by CERN RB in 2010 & reapproved for LHC's Run-3 in Dec. 2021

The Phase-0 MoEDAL Detector

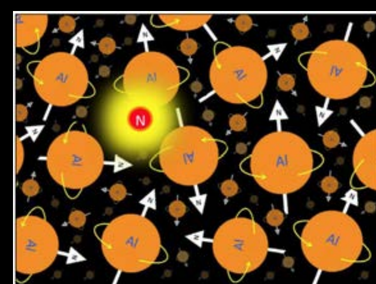
*Started data taking in (2011)2015– **the LHC's first dedicated search expt.***



--------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

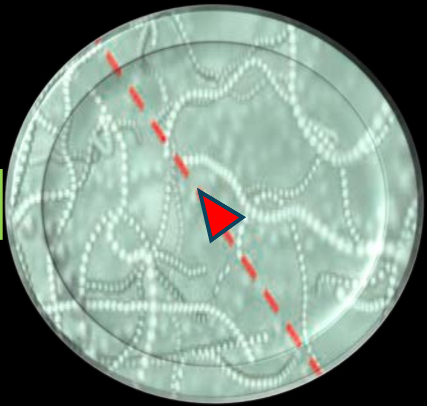
PERMANENT RECORD

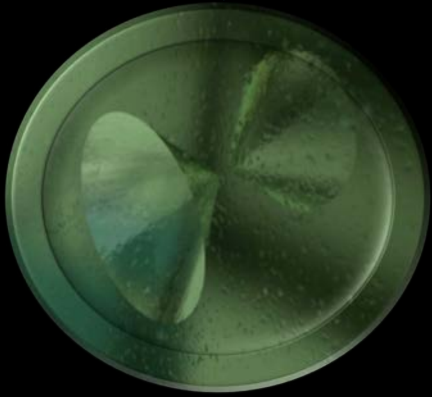
MoEDAL’s Remote Detector Facilities

NTD Processing - INFN Bologna

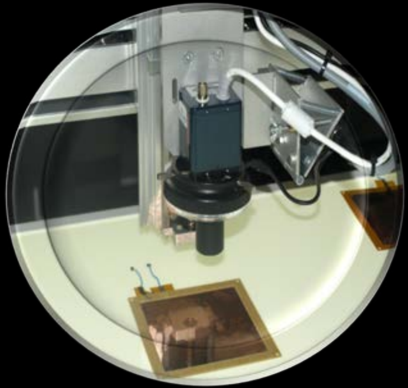
Etching in hot sodium Hrdroxide reveals damage

HIP causes damage Zone In NTD plastic





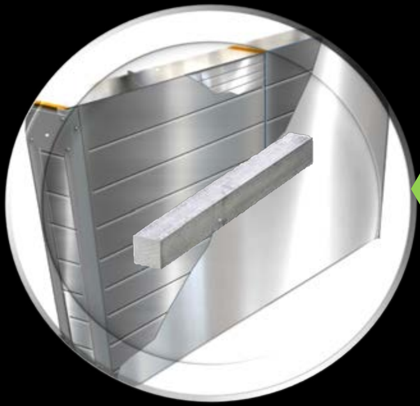
Etch pits reveal path and charge of HIP



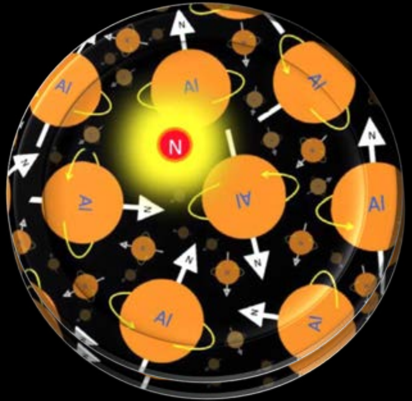
Etch pits measured by optical microscope

MMT Scanning- ETH Zurich

Trapping volumes are Removed for scanning



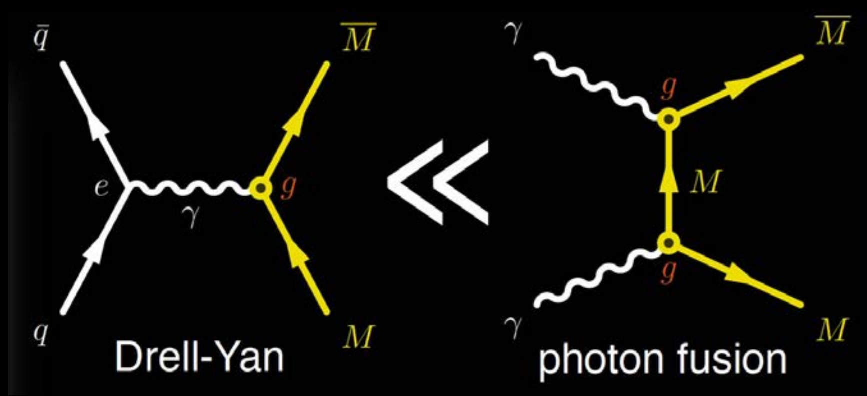
Monopole is trapped



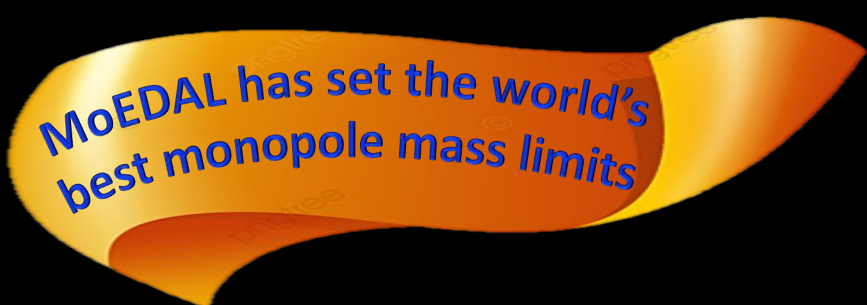
Trapping volumes are Passed through a SQUID

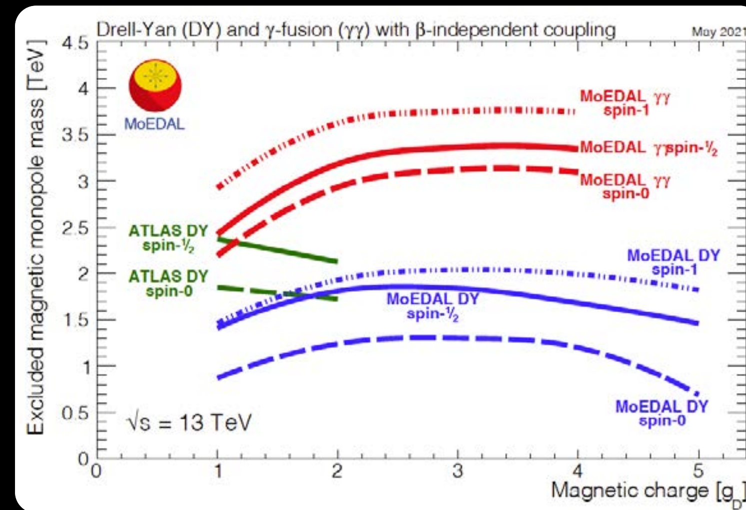
Monopoles cause a stable current in the SQUID

MoEDAL's Monopole Searches

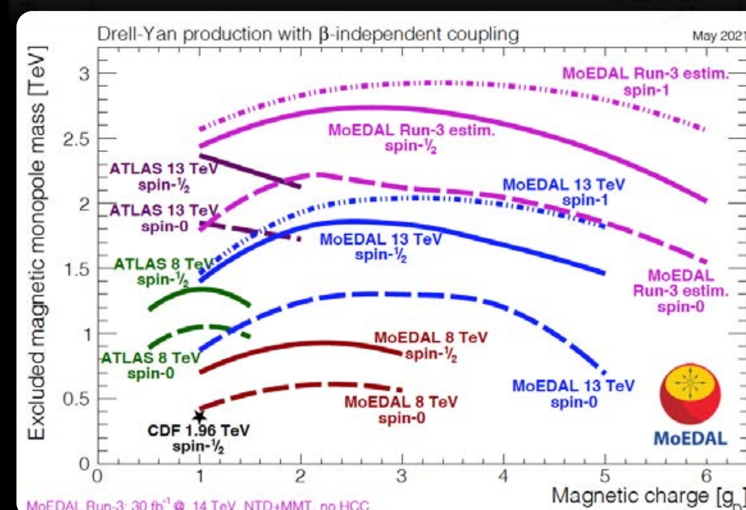


- *Unique features of MoEDAL's Search for Monopoles at the LHC*
  - *We consider β-dep./indep. couplings*
  - *Spin-1 monopoles*
  - *γγ fusion*
- *More results from Run-3 & HL-LHC*





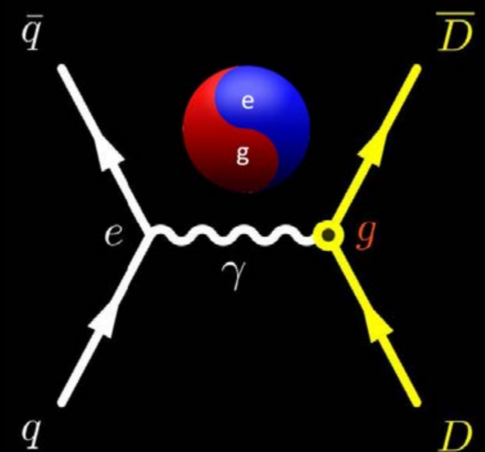
JHEP 1608 (2016) 067, PRL 118 (2017) 061801, PLB 782 (2018) 510, PRL 123 (2019) 021802, PRL 126 (2021) 071801

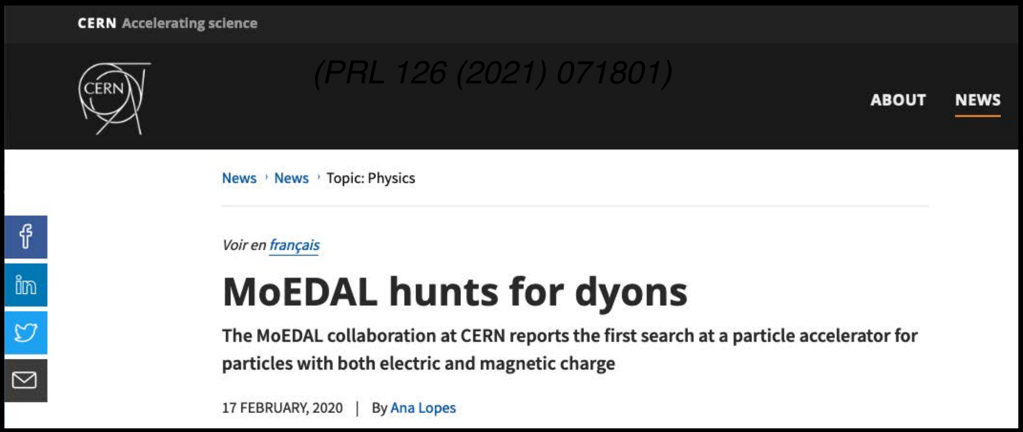


MoEDAL, Phys. Rev. Lett. 123 (2019) 021802.
Eur.Phys.J.C 78 (2018) 966

First Direct Search for the Dyon

MoEDAL




CERN Accelerating science

(PRL 126 (2021) 071801)

ABOUT NEWS

News › News › Topic: Physics

Voir en français

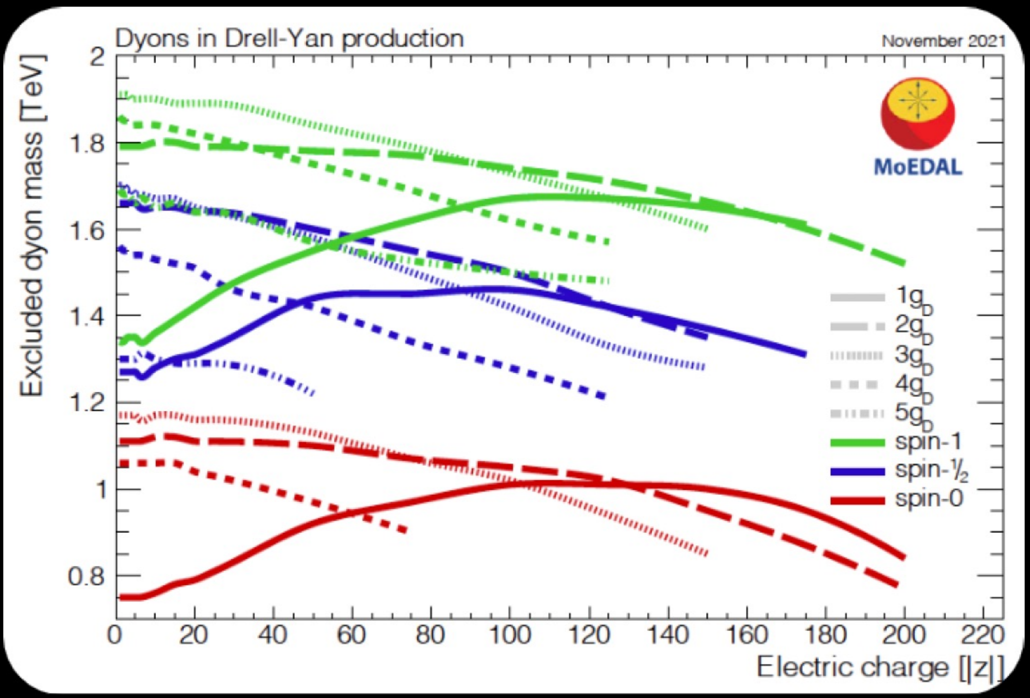
MoEDAL hunts for dyons

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

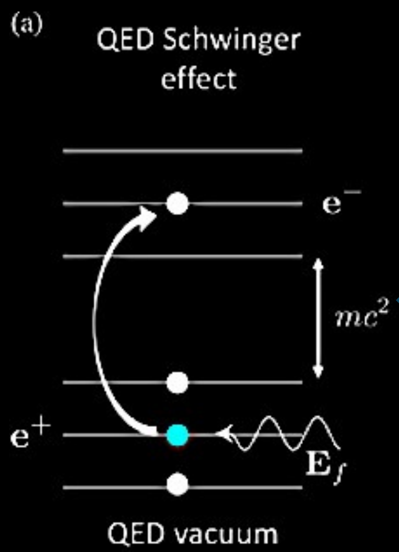
Predicted by Schwinger in 1969 a dyon has electric &magnetic charge

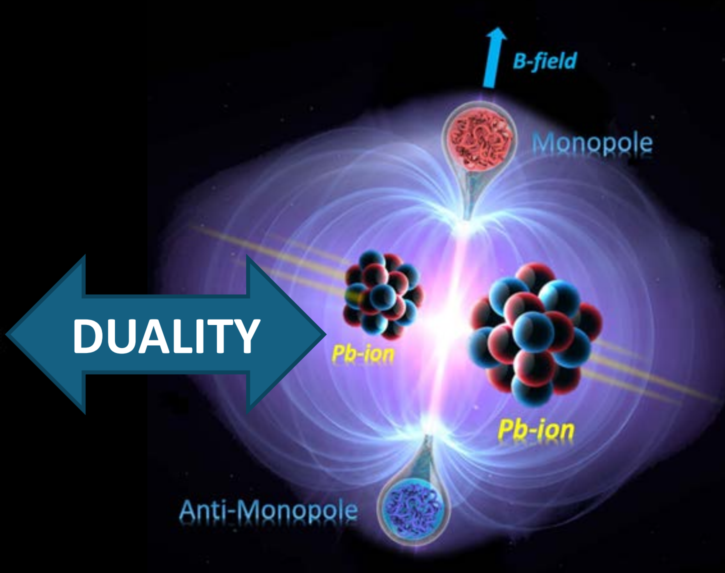
- *Mass limits 750-1910 GeV were set for dyons with ≤5g_D & electric charge ≤ 200e*

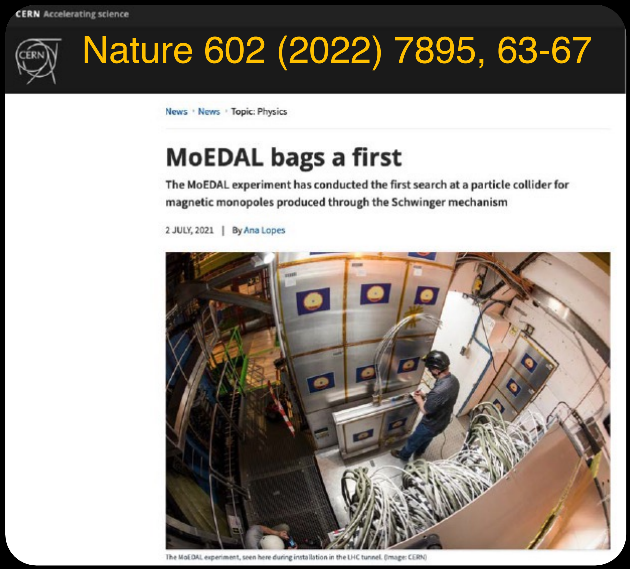


First ever explicit search for a dyon

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

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

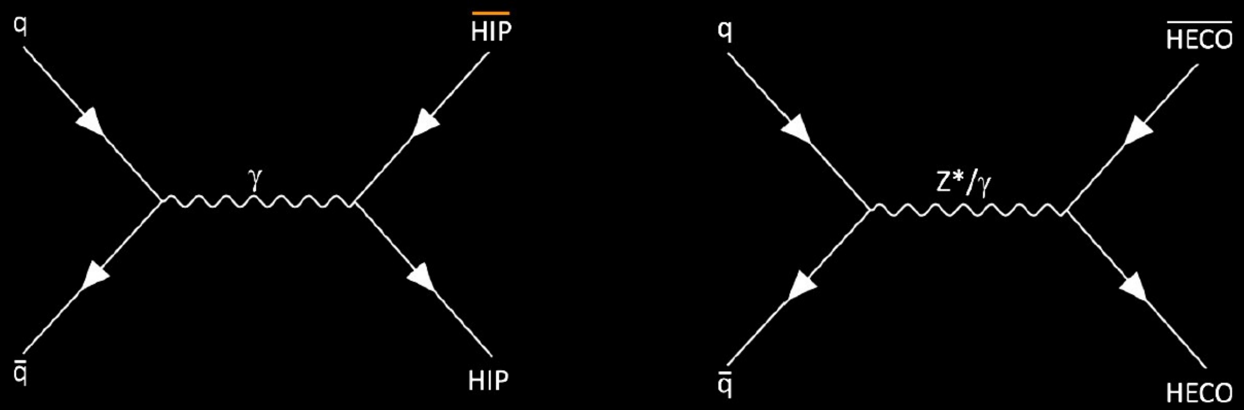
Pair production of monopole-antimonopole pairs in a very strong magnetic field created in ultraperipheral "collisions" of Pb-ions at the LHC can be as much as 10^{16}T.

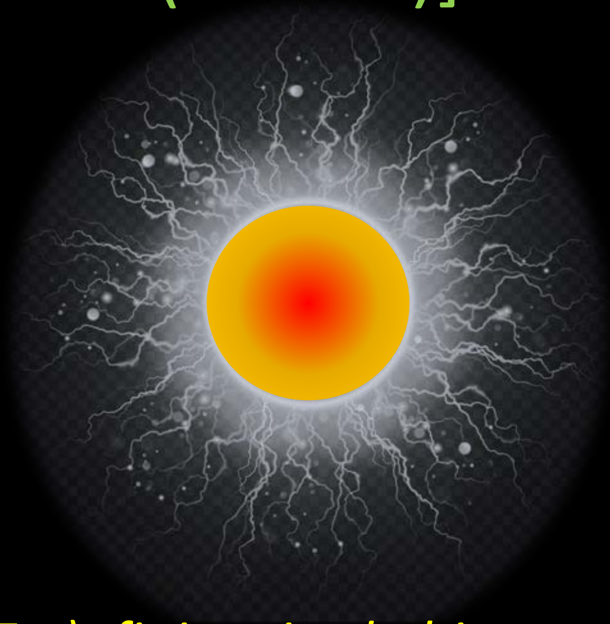
- ***Limits on Schwinger monopoles of 1 – 3 g_D and masses up to 75 GeV***
- *Advantages of Schwinger monopole production:*
  - *X-section calculation does not suffer from perturbative nature of coupling;*
  - *No exponential suppression for finite-sized monopoles.*

1st time finite sized monopoles detectable?

Searching for HECOs

[Highly Electrically Charged Objects (HECOs)]

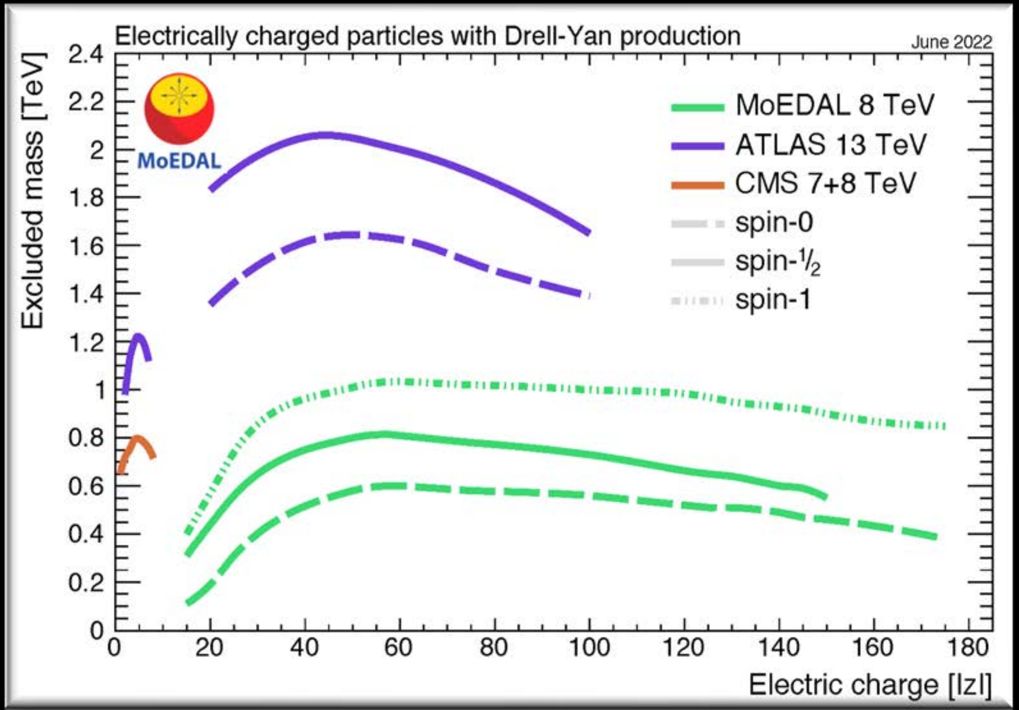


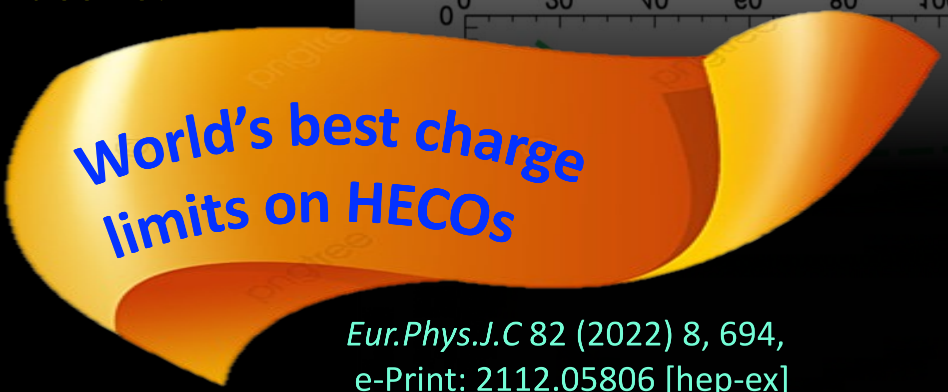


- *Highly Electrically Charged Objects (HECOs, Q > ~5e): finite-sized objects (Q-balls), condensed states (strangelets), microscopic black holes (through their remnants),etc.*
- *Drell-Yan production:*
  - *Z exchange is taken into account for fermions [Song, Taylor, J.Phys.G 49 (2022) 045002]*
  - *Non-perturbativity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

HECO Limits to Date

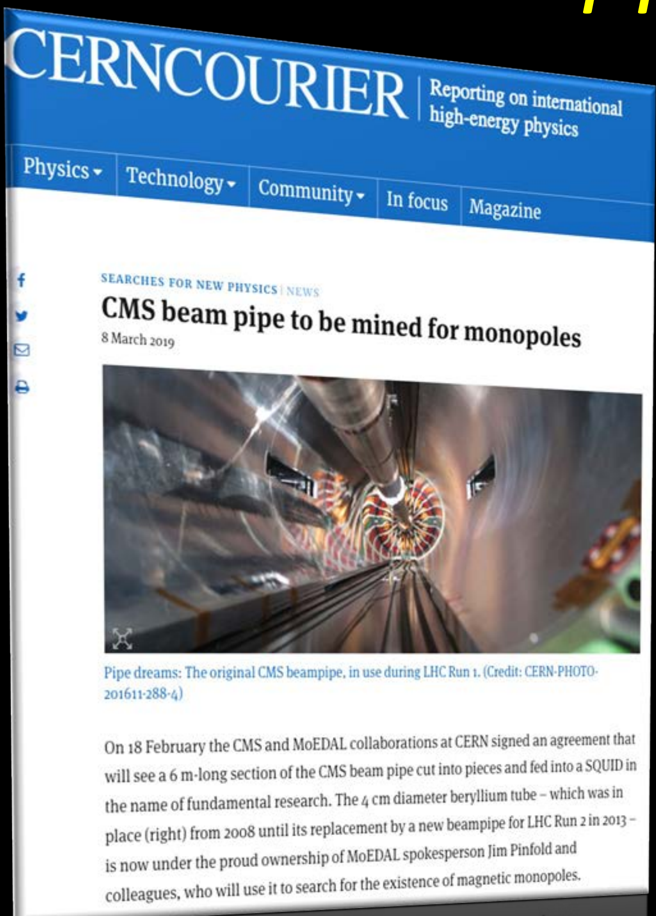
- *The MoEDAL prototype detetector at Run-1 set limits on HECOs with :*
  - *charge in the range 15e – 175e*
  - *masses from 110 – 1020 GeV*
  - *Limits set on HECO pairs with cross-sections from* ***~ 30 – 70 p***
- *Run-2 result out in a month or so with* ***full MoEDAL detector,*** *larger LUMI ,and higher* E_{cm} *➔much superior mass & charge limits*





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

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*

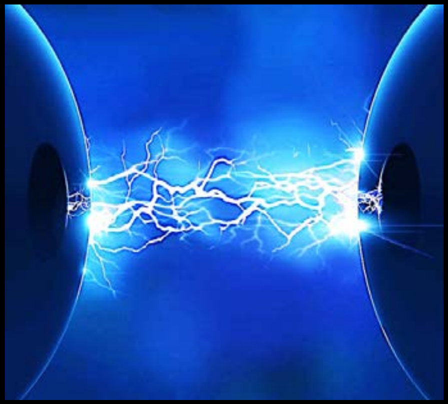
$$\Delta I = \frac{4\pi N}{L} g_D$$

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

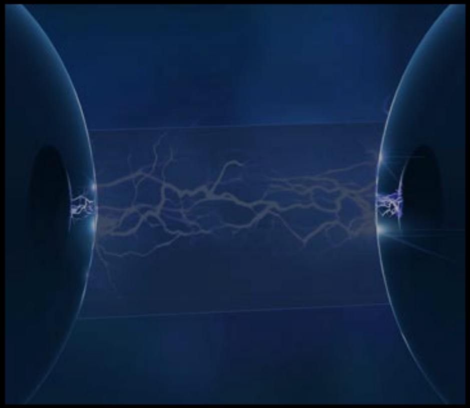
- *Analysis of the beampipe is underway*

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

The Physics Reach of MoEDAL-MAPP is increased to include:



Highly Ionizing Particles

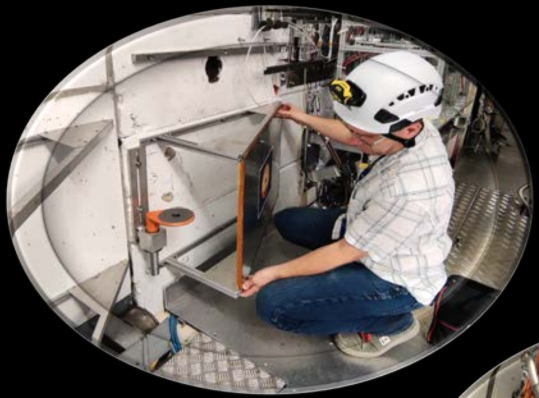


Feebly Ionizing Particles

Very Long-lived Particles

Upgraded MoEDAL Installed for Run-3

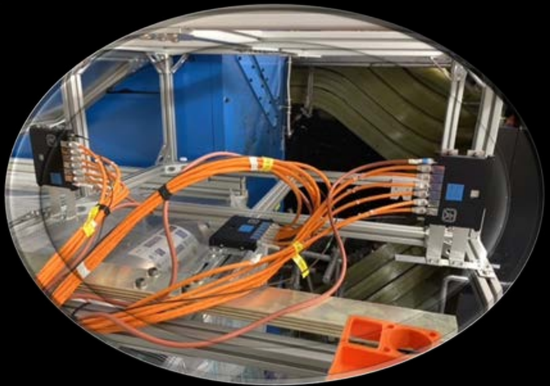
Upgrades to the Run-2 MoEDAL Detector, for Run-3 – completed in March 2023



NTD Stacks Point to IP

VELO-TOP NTD array installed

Forward MMT box reconfigured



TimePix3 Chips connected to LHC clock

The Search for Highly ionizing particles (HIPs) continues with:

- 5 x Higher Instantaneous Luminosity at IP8
- a) Improved Detector Efficiency b) X10 lower threshold
- Slightly higher Centre-of-mass Energy

MoEDAL

New Physics with Charge 1e—10e

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

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

MoEDAL detector optimised for HIP discovery with a detection threshold as low as ***z/β = 6***

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

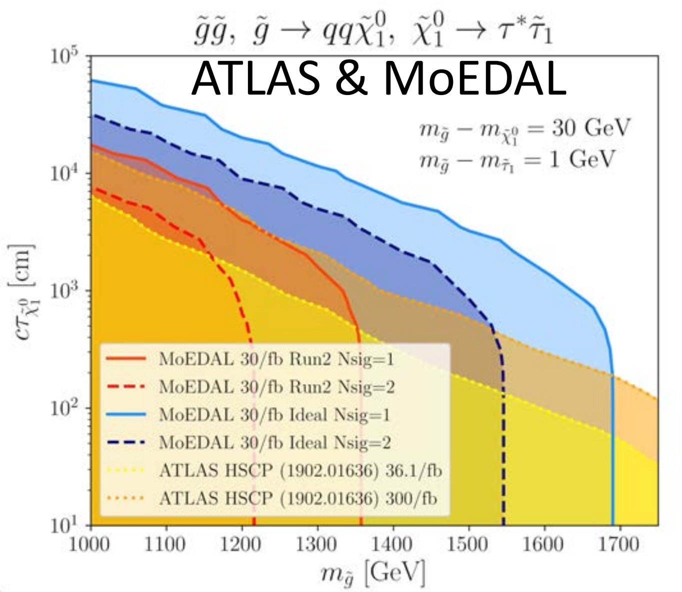
- *MoEDAL is background-free experiment → discovery scenarios require 1, 2 or 3 signal events*
- *Integrated luminosities at IP8 (LHCb/MoEDAL)*
  - *Run-3 increase in instantaneous luminosity by a factor of 5 → 30 fb^{-1}, roughly 10 times less than ATLAS & CMS*
  - *High Luminosity LHC (HL-LHC) → 300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

Detecting Long-lived SUSY Partners

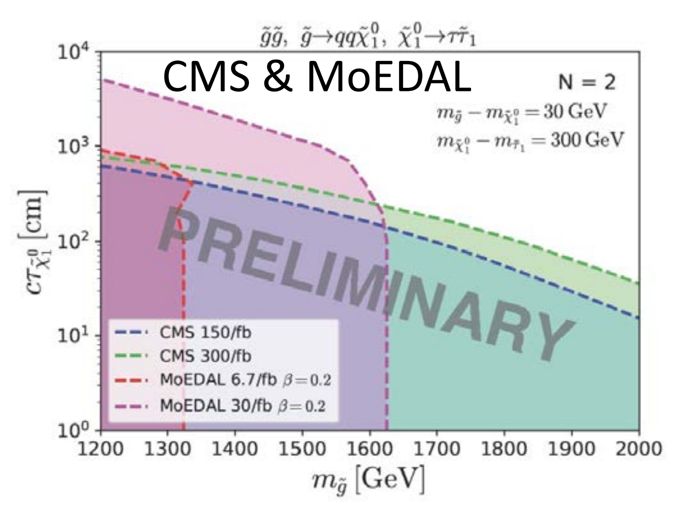
- *SUSY charged LLP states: sleptons, R-hadrons, charginos… sought at ATLAS & CMS*
- *For example, Benchmark decay chain: $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \tau^{\pm}\tilde{\tau}_1$*
  - *$\tilde{\chi}_1^0$ moderately long-lived → decays in the tracker of ATLAS/CMS*
  - *$\tilde{\tau}_1$ charged long-lived → interacts with detector ATLAS/CMS/MoEDAL*

Due to the absence of trigger, timing & SM backgrounds, MoEDAL can relax selection requirements + increase sensitivity to charged, SUSY LLPs

MoEDAL can cover long-lifetime region in Run2/3 at the LHC for gluinos, stops, sleptons and charginos



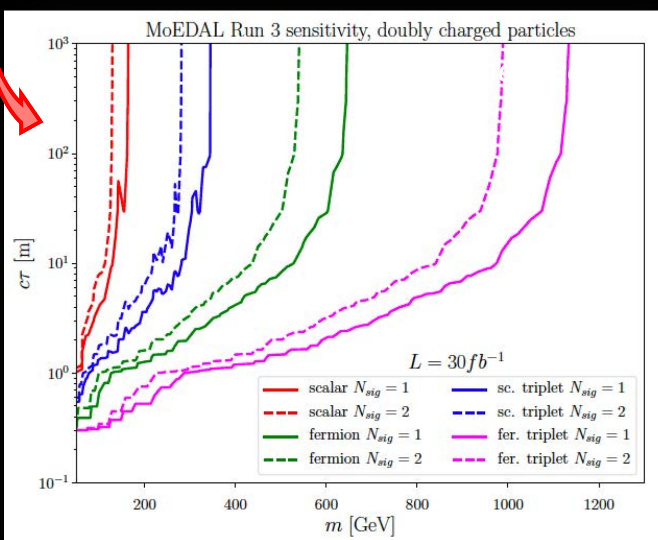
Felea, *et al*, EPJC 80 (2020) 431



Sakurai, *et al*, J.Phys.Conf.. 1586 (2020) 012018

Multiply Charged Particles – Specific Models

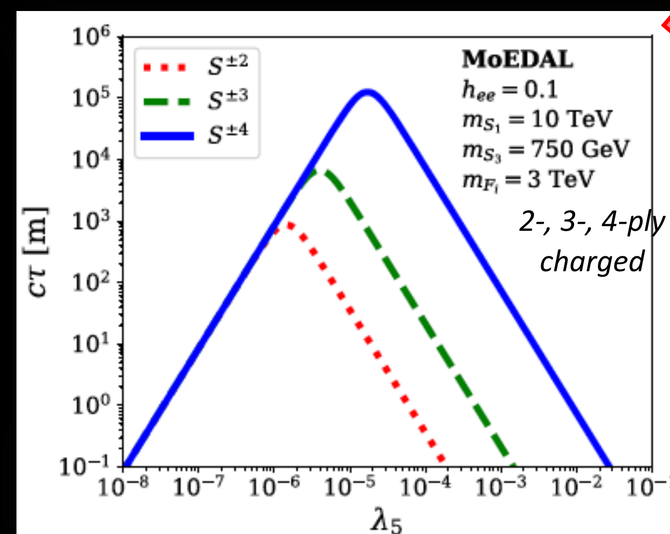
- Doubly charged particles
  - Predicted in left-right symmetric models, seesaw neutrino models, little Higgs models, … (+ SUSY extensions), extra dimensions, …
  - Models considered: (scalar, fermion) × (SU(2): singlet, triplet)
- 2-, 3-, 4-ply charged states occur in a class of neutrino mass models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



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

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

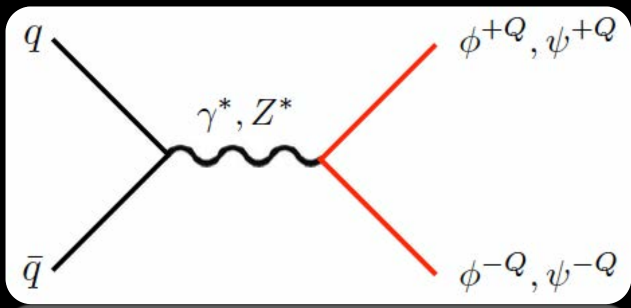


The λ_5 term breaks the lepton number symmetry and Is needed for neutrino mass generation

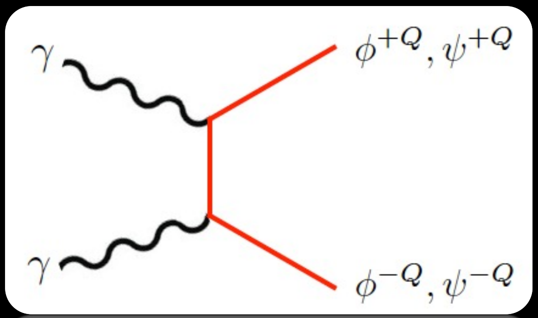
Hirsch *et al*, EPJC 81 (2021) 697

Multiply Charged Particles – Generic Case

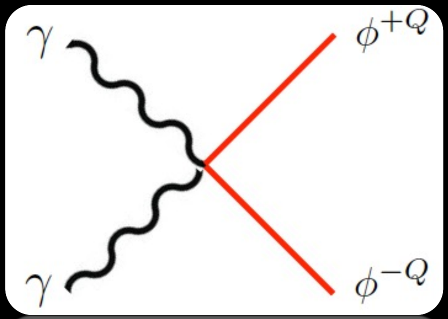
EPJC 82, 848 (2022)



s-channel (Drell-Yan)



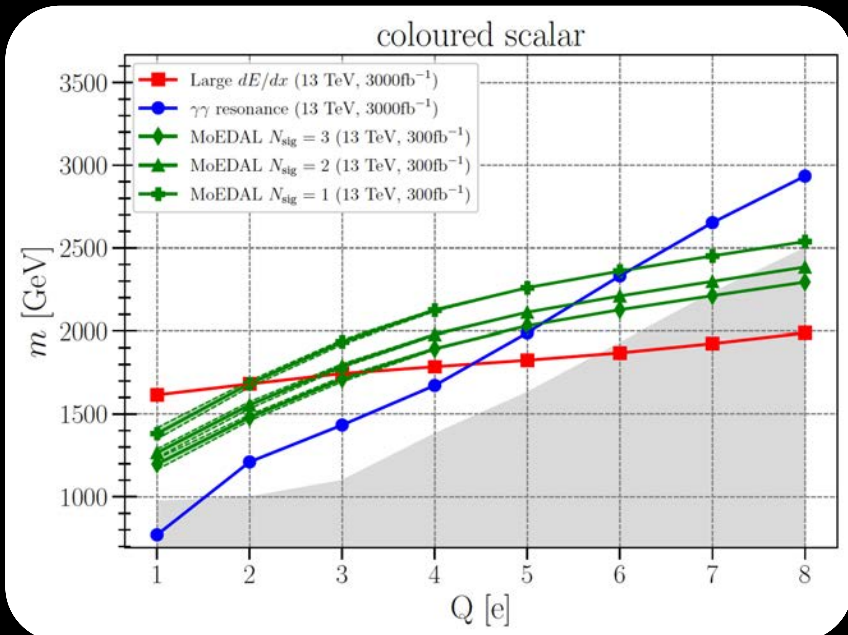
t-channel γγ fusion

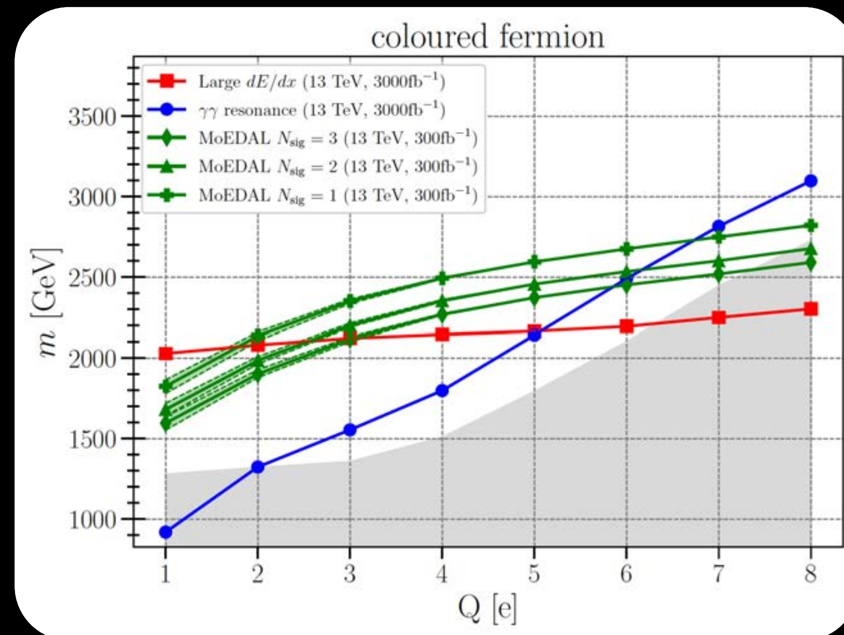


seagull γγ fusion (scalar only)

- *Phenomenological study largely 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.*

Multiply Charged Particles – Generic Case





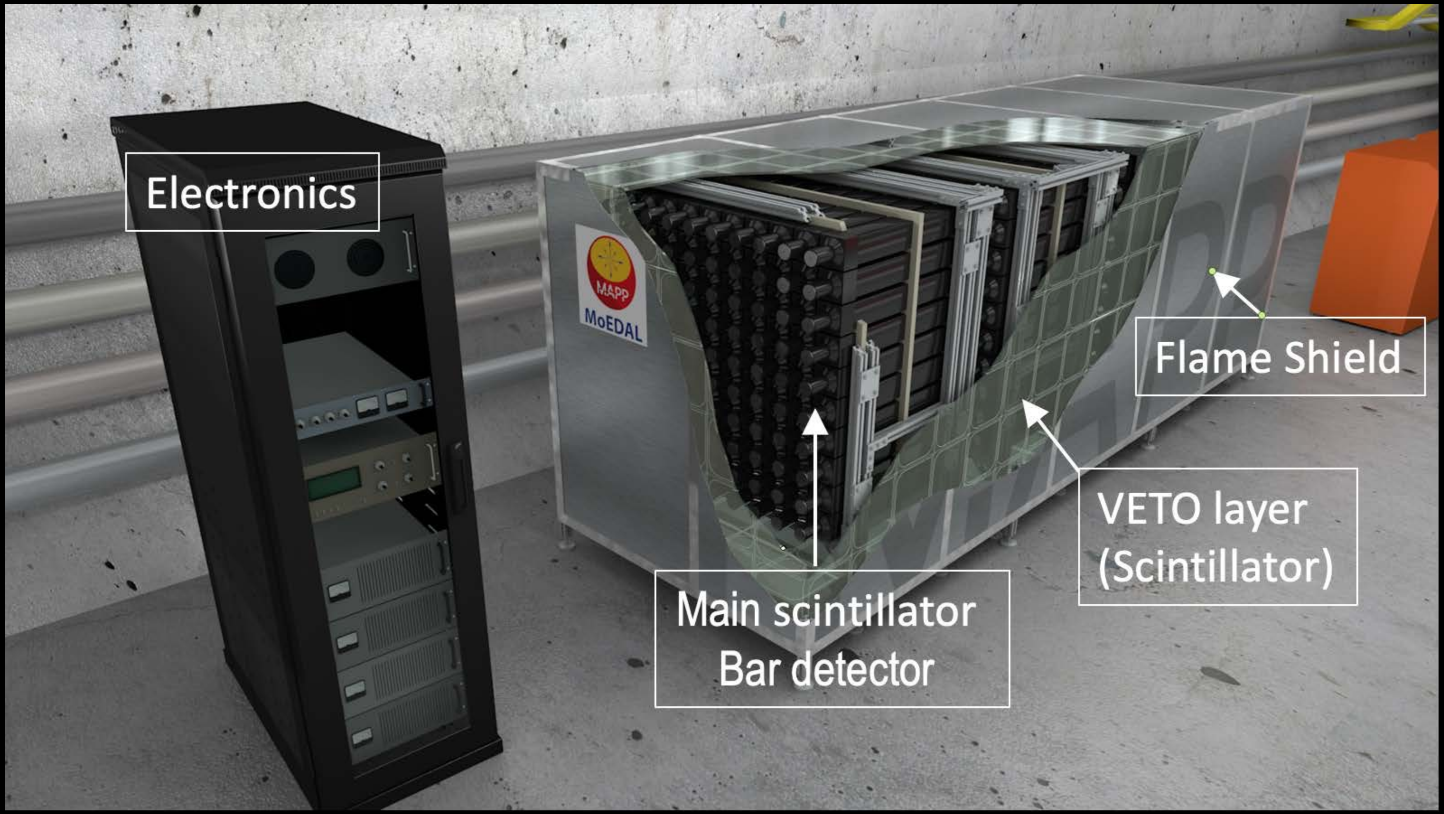
Altakach, Lamba, Masełek, VAM, Sakurai, Discovery prospects for long-lived multiply charged particles at the LHC, EPJC 82, 848 (2022)

- *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***

MAPP-1 is Currently Being Installed

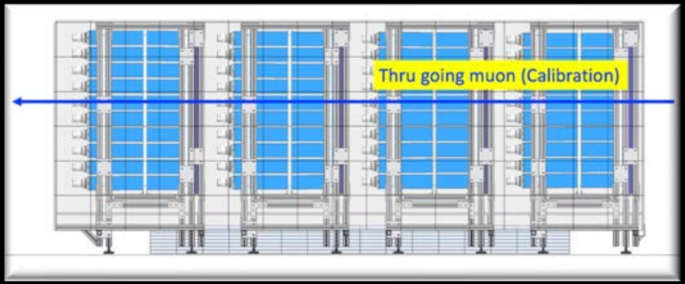
- *Installation proceeds when access to UA83 is permitted, the above photographs were taken in March 2023*
- *Installation continues during: June TS , Nov. TS and YETS in 2023*
- *We expect to take first data with complete detector in May 2024..*

The MAPP-1 Detector at UA83

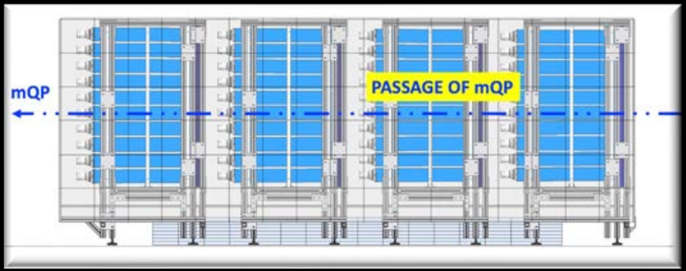


- 400 scintillator bars (10 x 10 x 75 cm^3) in 4 sections readout by PMTs - Protected by a hermetic VETO counter system
- Each through-going particle sees 3m of scintillator readout by a coincidence of 4 low noise PMTs

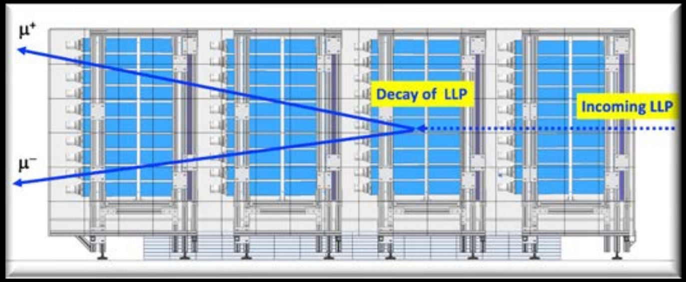
MAPP – Modes of Detection



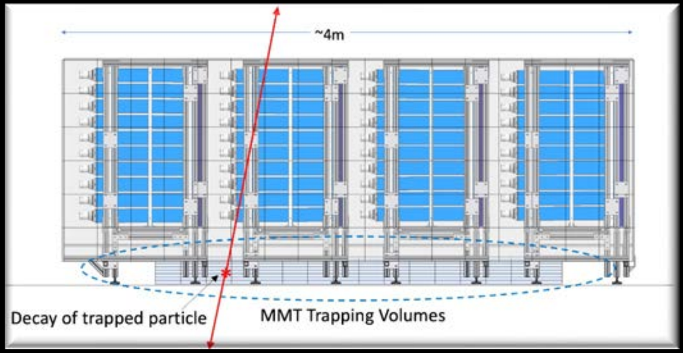
Muons from IP (Calibration)



Millicharged particle detection

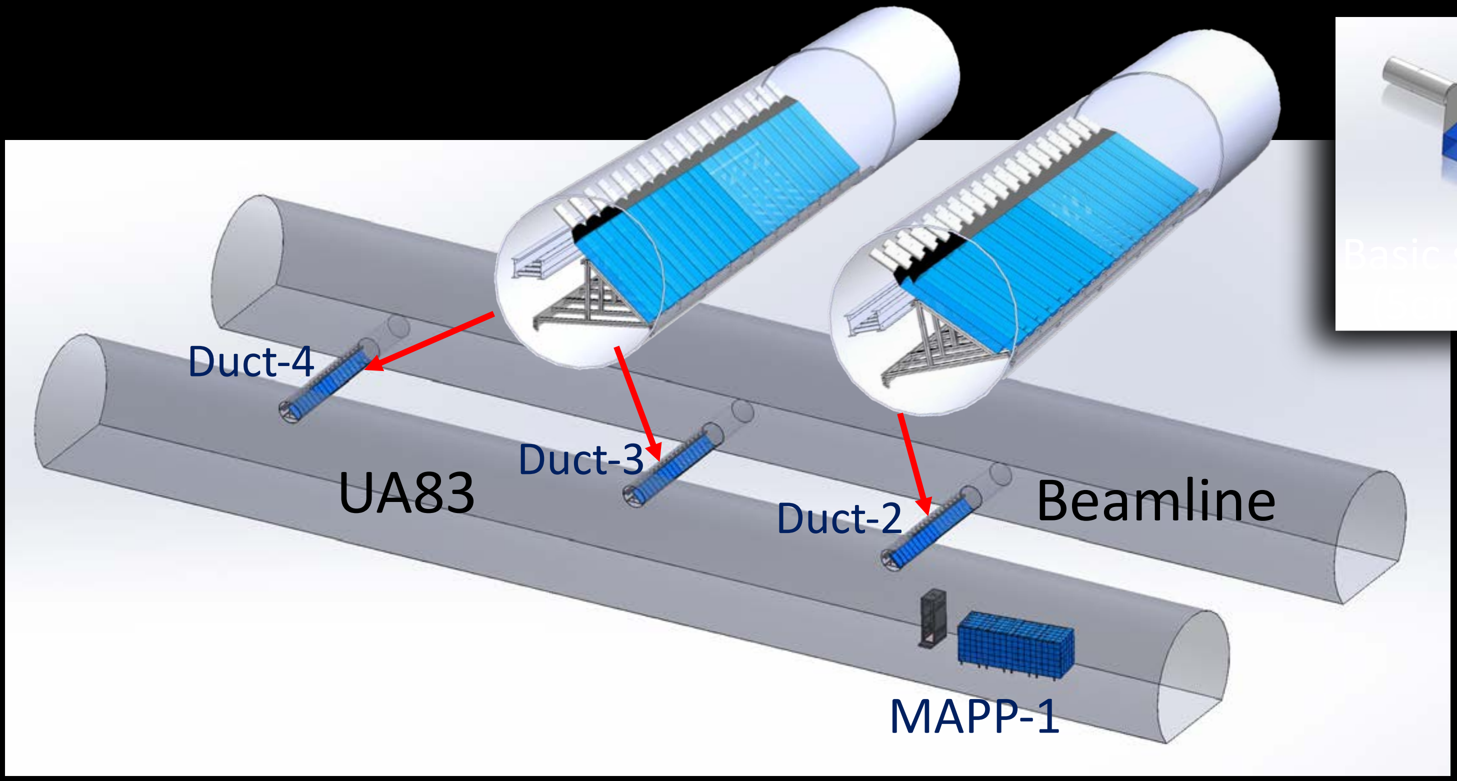


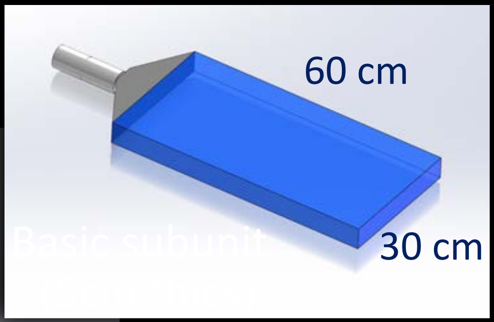
Neutral LLP Detection



Charged LLP Detection
(In conjunction with MoEDAL)

The MAPP-1 Outrigger Detector

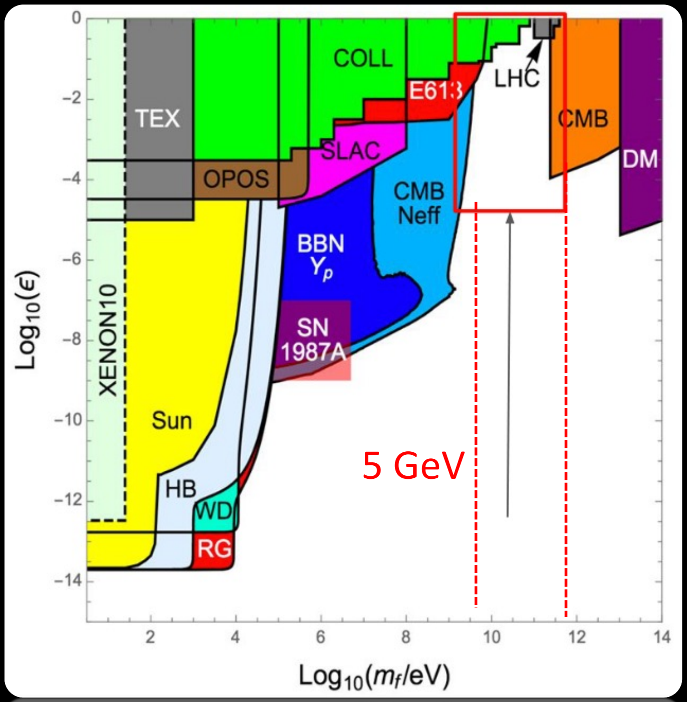




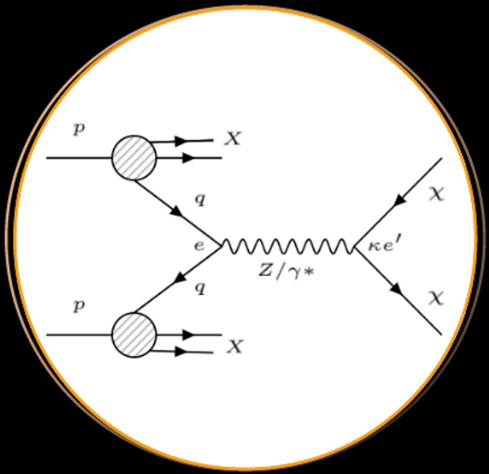
- *The outrigger's purpose is to increase the acceptance of MAPP-1 at higher mass & larger fractional charge*
- *Size of the scintillator "planks" 6m x 0.6m x 5 cm, inclined at 45 deg.*
- *Covers from ~1.7 deg. to 5.3 deg.*

Production of Milli-charged at Colliders

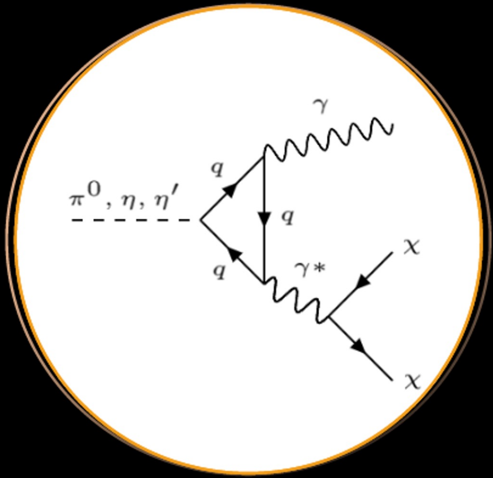
mCPs arise naturally from the dark sector eg via the Vector Portal/Dark Photon



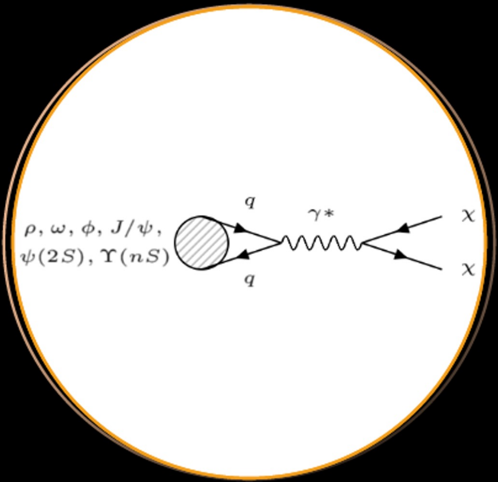
The Sweet Spot
arXiv:1511.01122



Via the Drell Yan Process

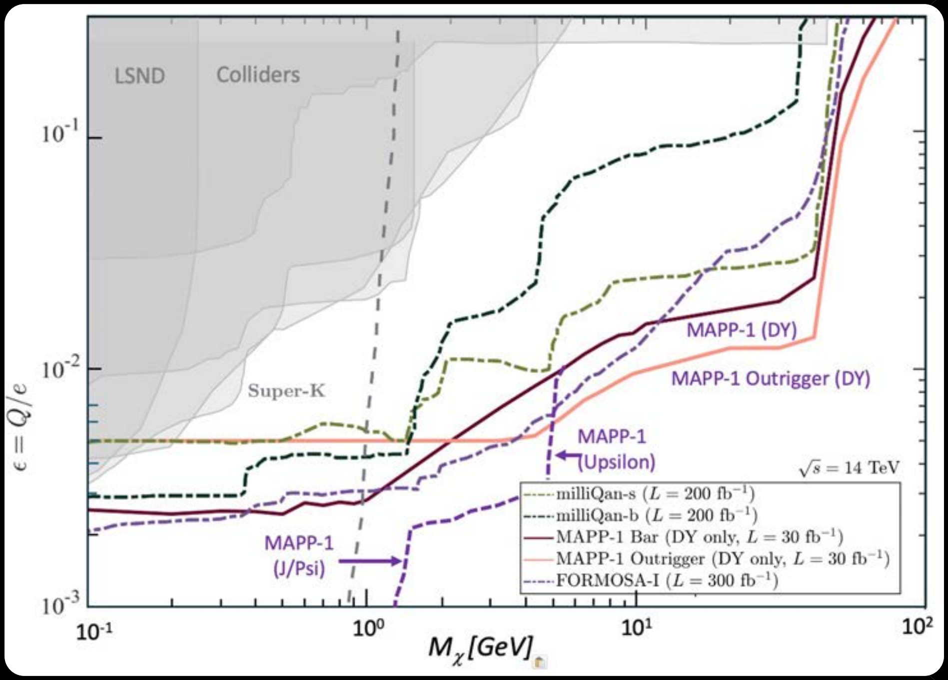


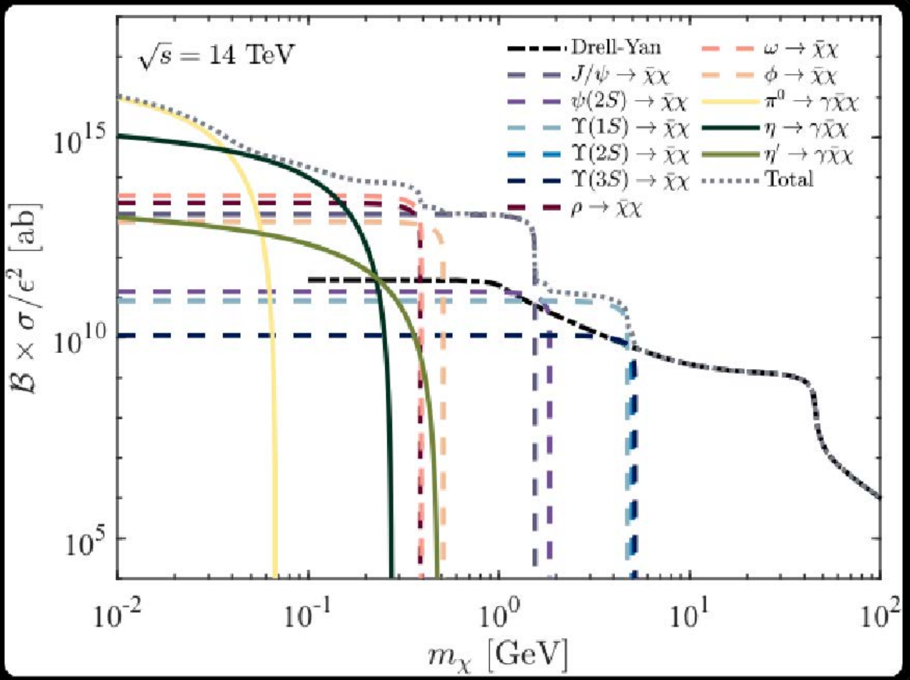
Via pseudoscalar meson Dalitz decays



Via direct decays of vector mesons

EG: MAPP-1 mCP Physics Sensitivity

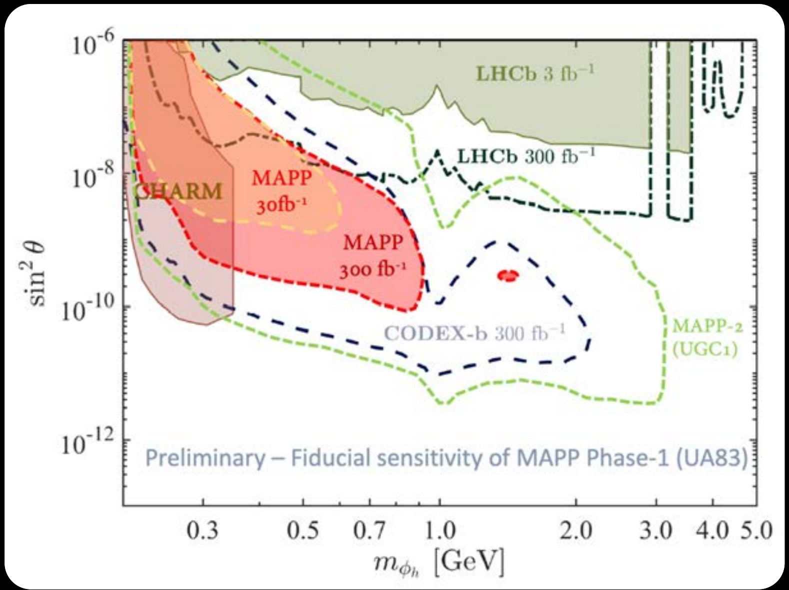




- *LEFT: Estimated reach of MAPP-mCP at √ s = 14 TeV for HL-LHC*
    - *The outrigger detector enhances the sensitivity at higher mass*
- *RIGHT: the addition of the resonances and meson decays to mCPs enhances the number of lower mass mCPs*
- *CAVEAT: At present the MAPP-mQP plots assumes 100% detector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

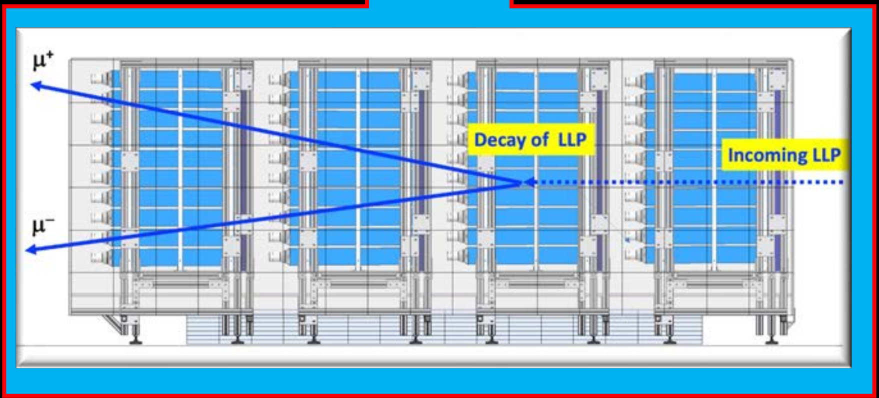
MAPP-1: LLP Physics Examples

Neutral LLPs

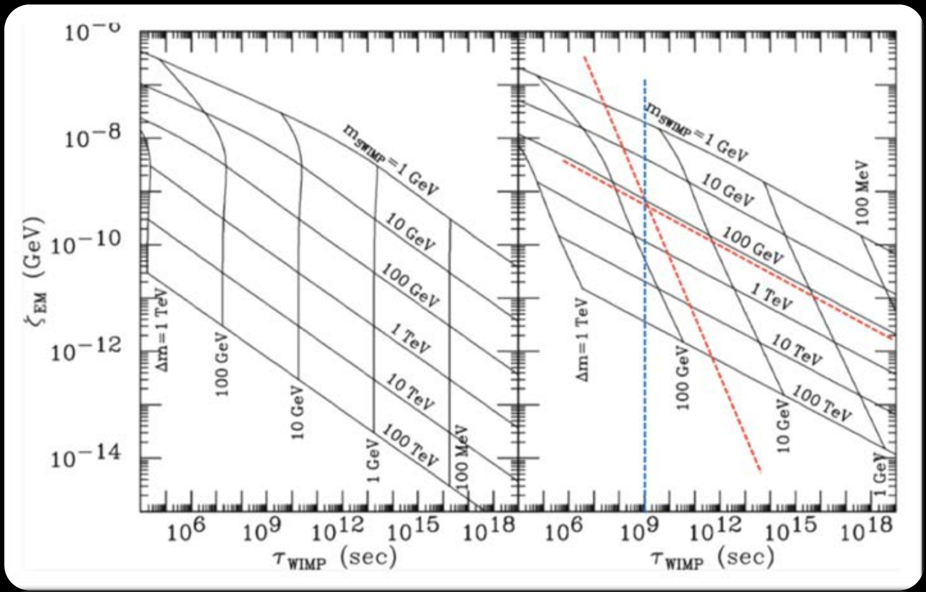


Phys. Rev. D, 97:015023, Jan. 2018.

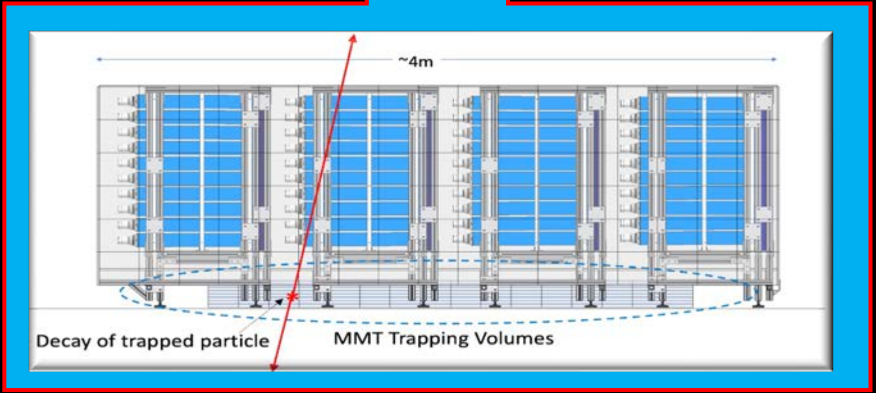
$B \rightarrow X_s\phi_h$, $\phi_h \rightarrow \mu^+\mu^-$ (ϕ_h is a light scalar that mixes with the Higgs



Charged LLPs (superWIMPs



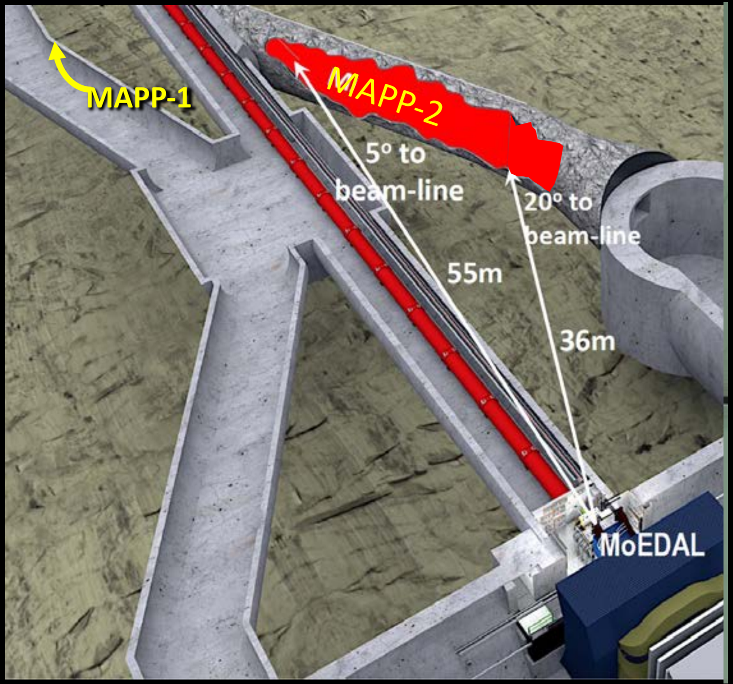
J. L. Feng, A. Rajaram Phys. Rev. D 68, 063504 (2003).

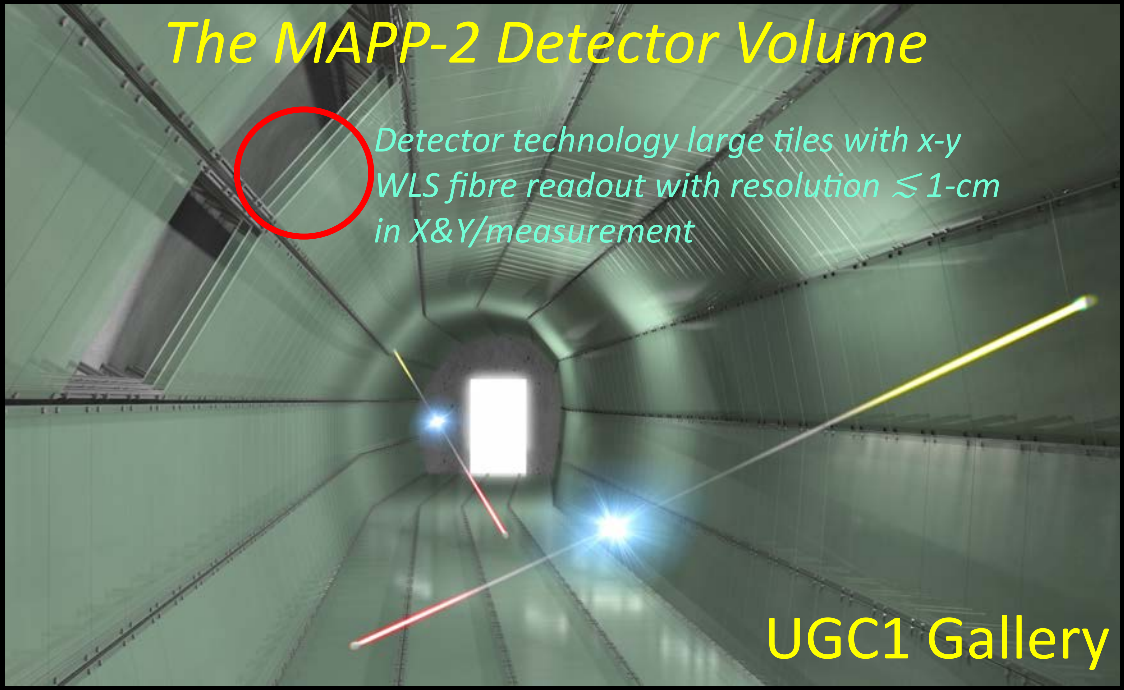


The MAPP-2 Upgrade for the HL-LHC -- back to UGC1

The search for HIPS and FIPs will continue to high luminosity at HL-LHC. The MAPP-2 detector at UGC1 will be installed to drastically increase sensitivity to long-lived particles

Phase-2: MAPP-2 for HL-LHC



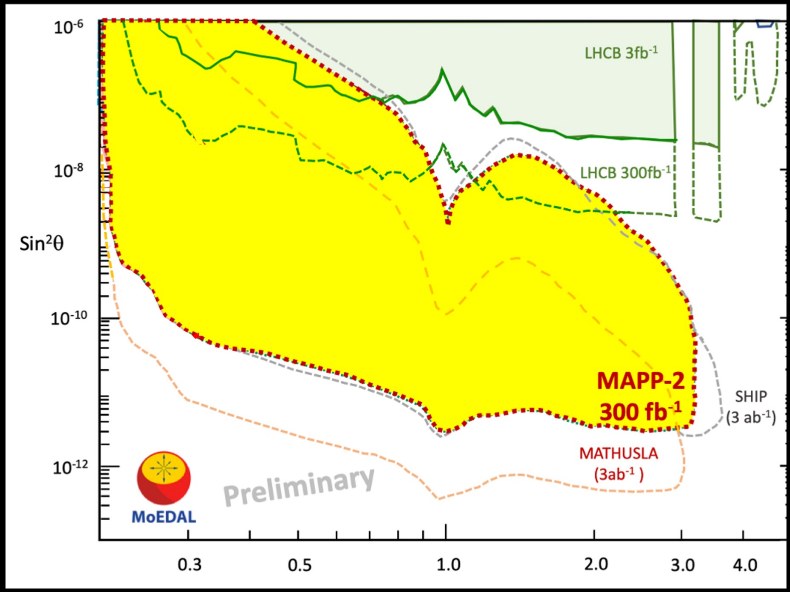


- *The MAPP-2 detector would fill the UGC1 gallery adjacent to LHCb*
  - *The UGC1 gallery would be prepared during LS3 prior to HL-LHC*
  - *The tracking detectors would form 3 or 4 hermetic containers - one within the other – lining the walls of UGC1*
- *MAPP-2 ~1200 m^3 of instrumented decay volume. Estimated technical*
- *Costs of MAPP-2 ~$3-4 M including 0.5K of civil engineering.*

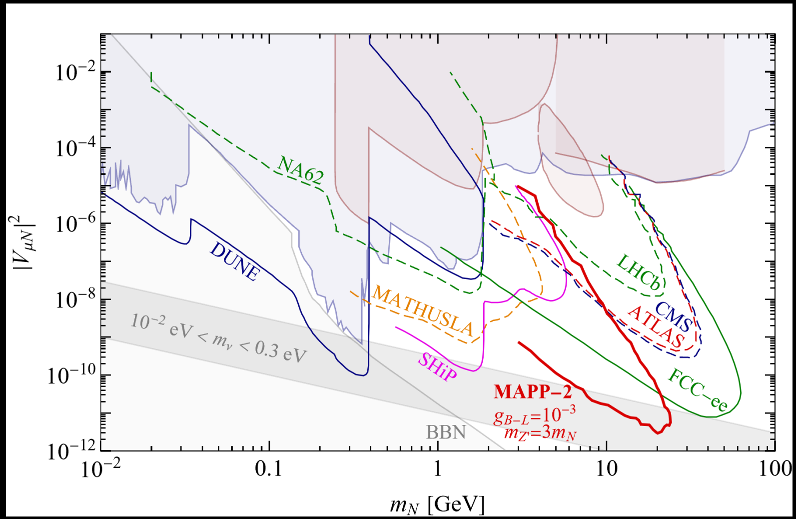
MAPP-2: Example Physics Studies

- *Benchmark process:*
  - *The Higgs mixing portal admits inclusive B → $X_s\phi$ decays, φ is a light scalar that mixes with the Higgs (mixing angle $\vartheta \ll 1$)*
- *TOP: MAPP-2 each for 300 fb^{-1} compared to CODEX-b, SHIP, MATHUSLA.*
- *Bottom: Pair production of RH 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*
- *In this example vomplementary 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.



Frank Deppisch, to be published in EPJ-ST

Concluding Remarks

With dedicated detectors such as MoEDAL-MAPP as our new eyes we h
to reveal physics beyond the SM illumination

EXTRA SLIDES

Summary

PHASE-0 (LHC Run-1 & 2)

MoEDAL – Optimized for HIPs

- World's best limits on multiply charged MMs
- First ever search for Schwinger MM prod.
- Best charge limits on highly charged particles
- First ever search for dyons
- Even better limits from final Run-2 results

PHASE-1 (LHC Run-1 & 2)

MoEDAL – Upgraded

- Continue search for HIPs
- Competitive sensitivity for heavy singly & multiply charged LLPs

MAPP-1 – Optimized for mCPs

- Timely sensitivity to Neutral LLPs
- Competitive reach for charged VLLPs

ATLAS & CMS

Optimized for

Relativistic SM particles from the IP, with:

1) Charge ± 1e or 0
2) Stable or with t $\lesssim$ ps

PHASE-2 (HL-LHC Run-4 & Beyond)

MAPP-1 - Hi Lumi

MoEDAL - Hi Lumi

MAPP-2 – Optimized for neutral LLPs

- Back to UGC1
- Competitive & complementary and cost effective
- search for neutral LLPs