LLPs in MoEDAL-MAPP

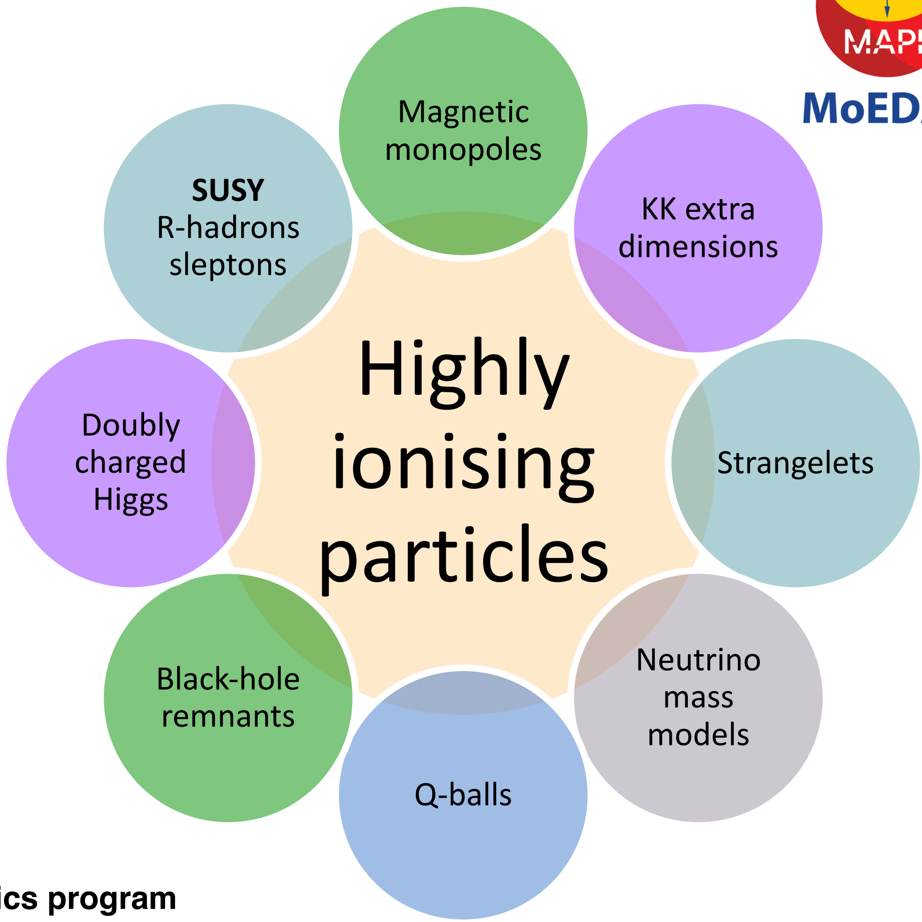
Vasiliki A. Mitsou

for the MoEDAL-MAPP Collaboration

MoEDAL physics goals

- MoEDAL baseline detector optimised for the detection of (meta)stable **highly ionising** particles
  - high charges (**high z**)
    - magnetic → **monopoles**!
    - electric → Highly Electrically Charged particles (**HECOs**)
  - slow moving (**low β**) ⇒ massive

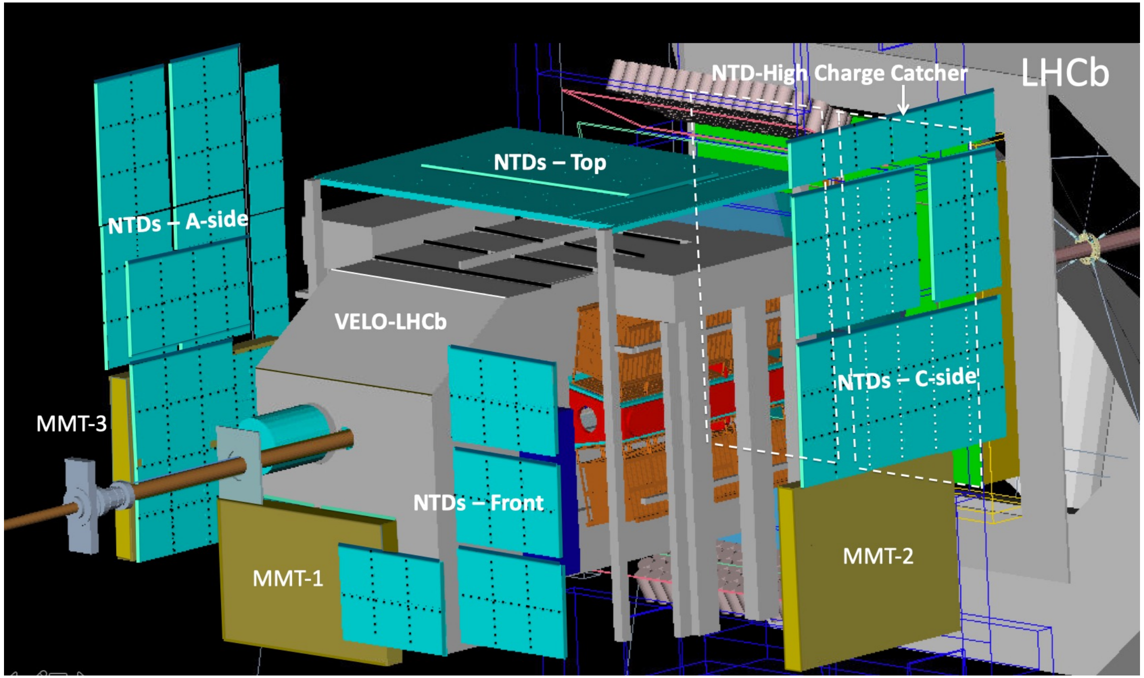
- **MAPP upgrade designed for *neutral LLPs* and *millicharged* particles**



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

Baseline MoEDAL detector

MoEDAL



Situated @ LHC IP8 (LHCb)

DETECTOR SYSTEMS

① Nuclear Track Detectors (**NTD**)

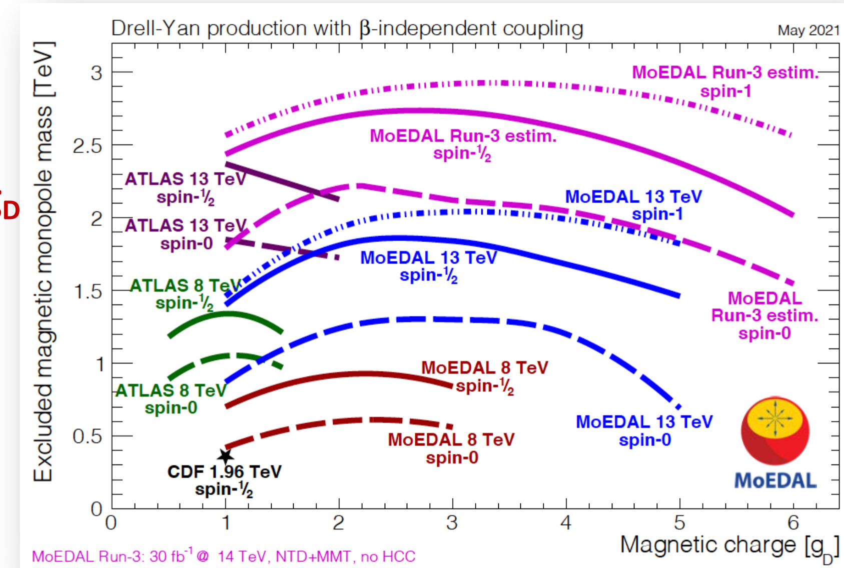
② Monopole Trapping detector (**MMT**) – aluminum bars

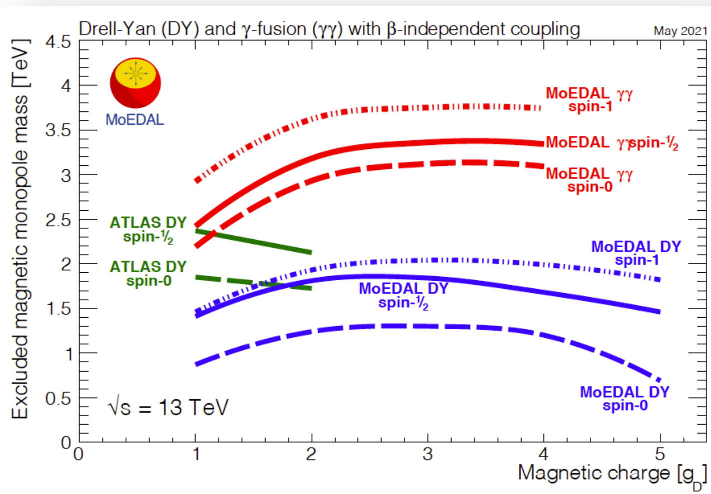
③ **TimePix** radiation background monitor

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

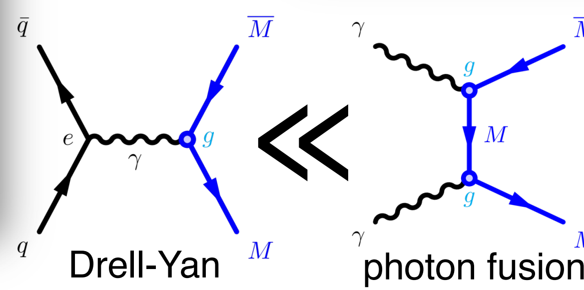
Magnetic monopole limits

- Novelties in models: β-dependent coupling, spin-1 monopoles, γγ fusion
- MoEDAL set world-best collider limits for **|g| > 2 g_D**
- Overall, MoEDAL achieved extended reach by **combining Drell-Yan and γ-fusion mechanisms**



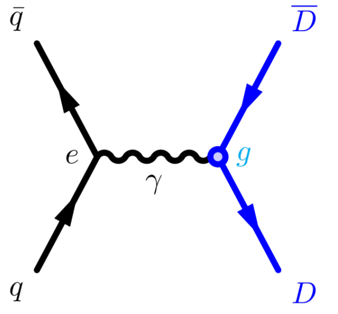


See also, Baines, Mavromatos, VAM, Pinfold, Santra, [Eur.Phys.J.C 78 (2018) 966]



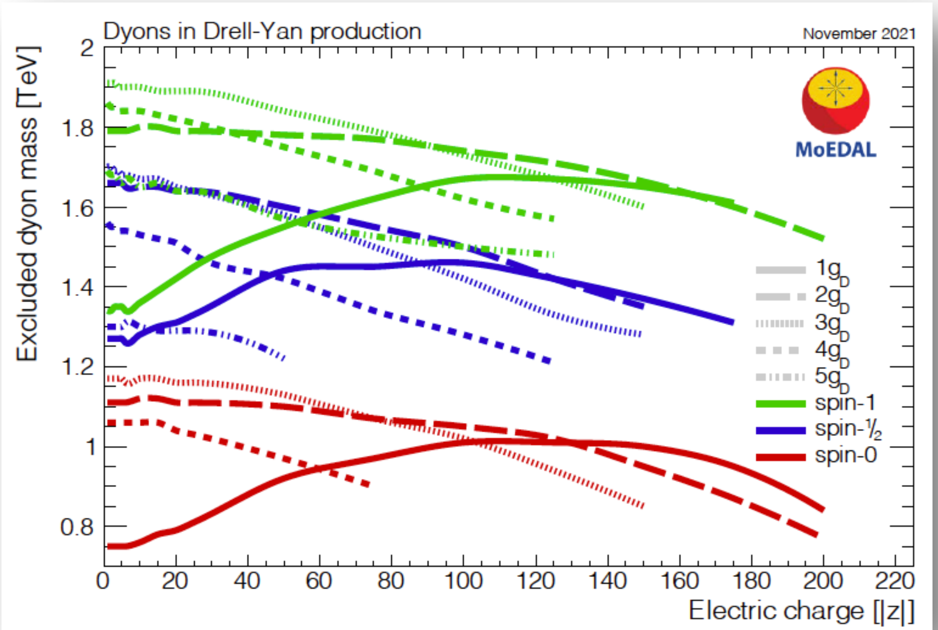
MoEDAL, [JHEP 1608 (2016) 067], [PRL 118 (2017) 061801], [PLB 782 (2018) 510], [PRL 123 (2019) 021802], [PRL 126 (2021) 071801]

Dyons: electric & magnetic charge



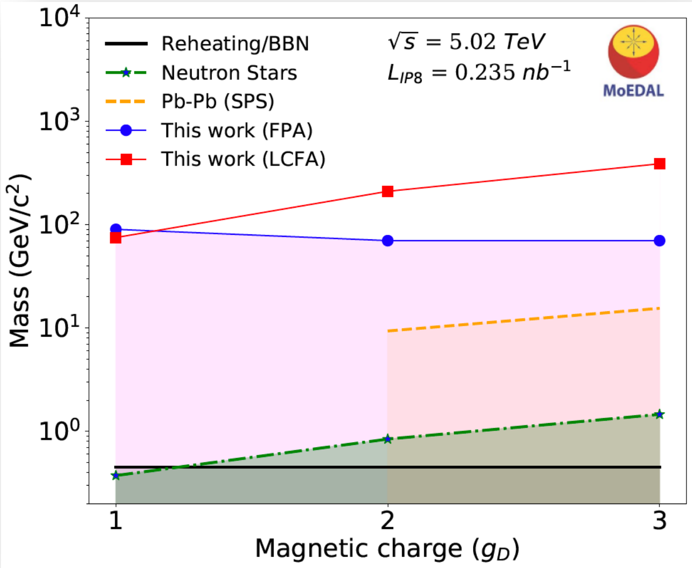
- MMT scanning searching for captured dyons
- Mass limits **750-1910 GeV** set for dyons with
  - up to 5 Dirac magnetic charges (**5g$_D$**)
  - electric charge **1*e* – 200*e***
- Excluded cross sections as low as **30 fb**
- Previous searches for highly ionising particles would, in principle, also have sensitivity to dyons
  - caution on behaviour under magnetic field

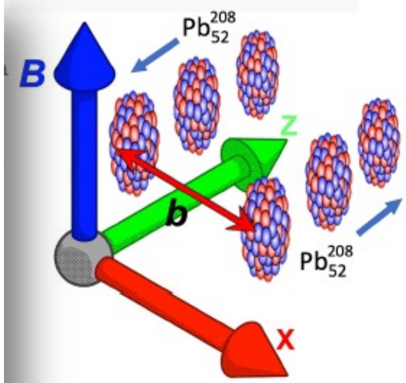
First explicit accelerator search for direct dyon production!



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

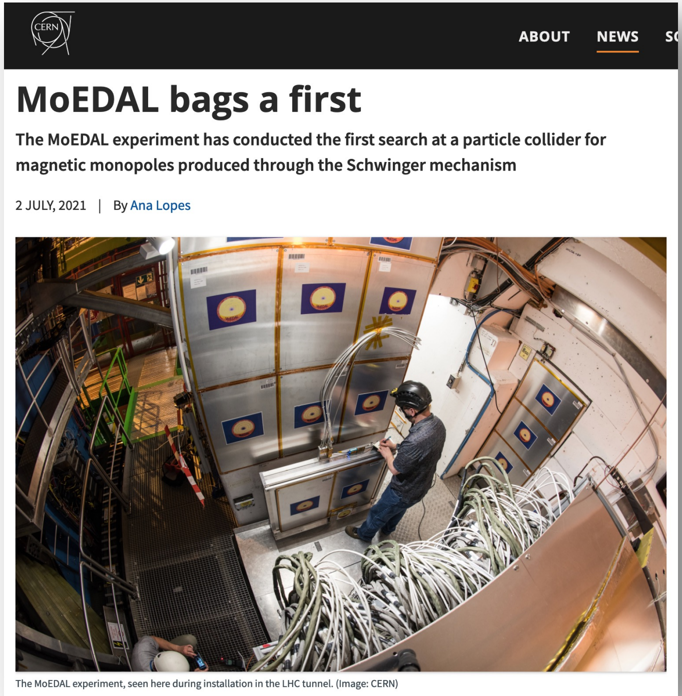
Monopoles via thermal Schwinger mechanism





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

Limits on monopoles of 1 – 3 g_D and masses up to 75 GeV


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)

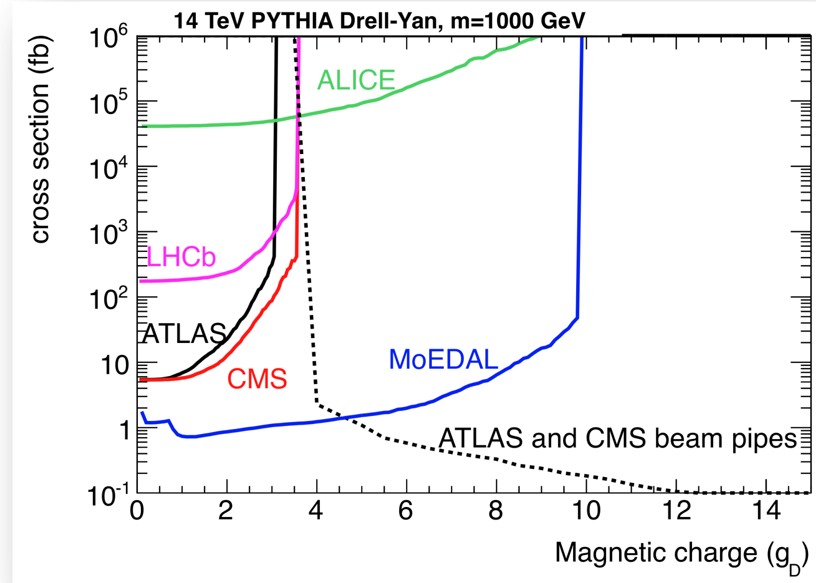
- First limits based on non-perturbative calculation of monopole production cross section
- First direct search sensitive to finite-size monopoles

MoEDAL, Nature 602 (2022) 7895, 63-67

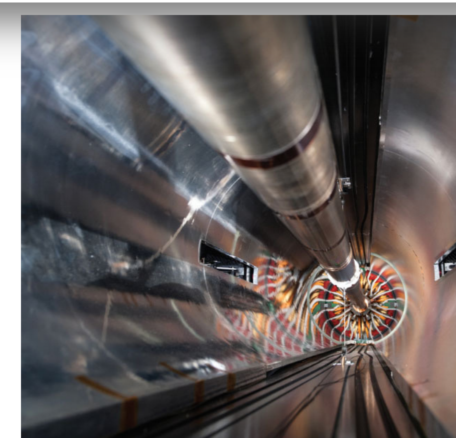
CMS beam pipe

Beam pipe
- most directly exposed piece of material
- covers very high magnetic charges

- **2012:** first pieces of CMS beam pipe tested [EPJC72 (2012) 2212]
  - far from collision point
- **Feb 2019:** CMS officially transfers ownership of the Run-1 CMS beam pipe to MoEDAL



De Roeck et al, EPJC72 (2012) 1985

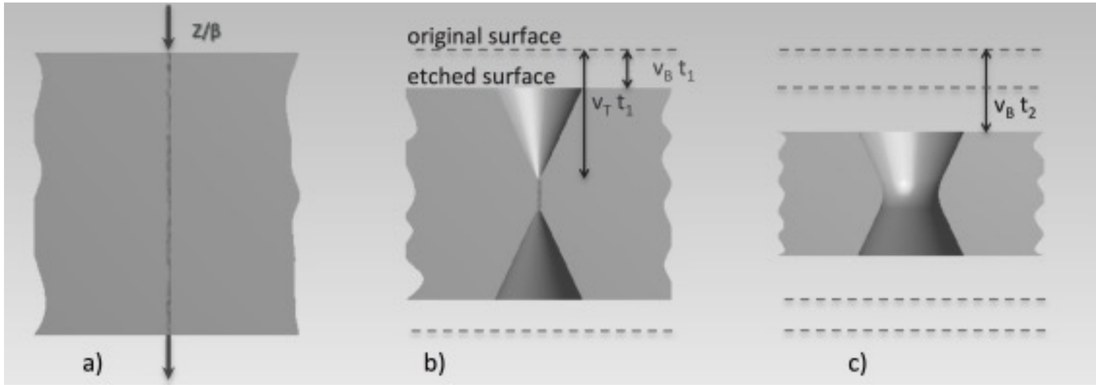


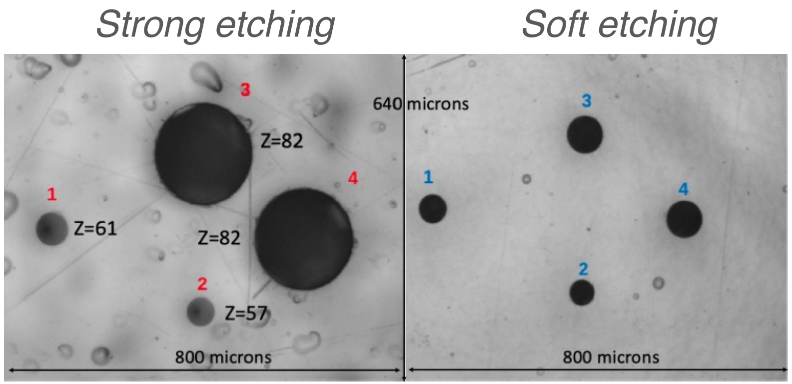
CERN Courier, Mar-Apr 2019

- Beam pipe scanned with SQUID at ETH Zurich
- Analysis for Pb-Pb collision data ongoing
- **Schwinger mechanism** assumed
- Results to be released soon

High Electric Charge Objects (HECOs)

- **First NTD analysis for MoEDAL**
- Prototype NTD array of 125 stacks ($7.8\ m^2$) in Run-1
- NTDs etched and scanned





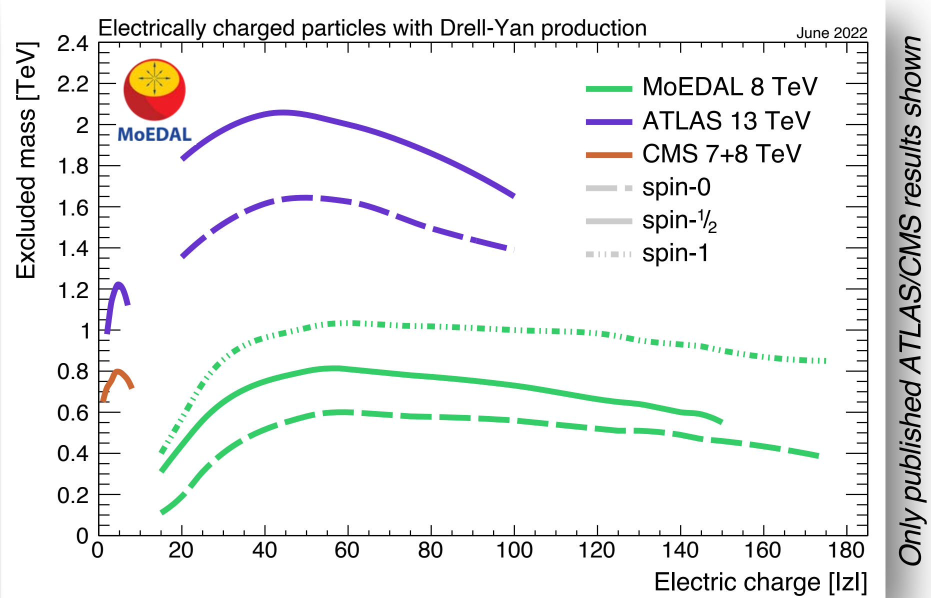
Calibration with 158 A GeV Pb^{82+} and 13 A GeV Xe^{54+} ion beams

No HIP candidates found in the NTDs stacks

MoEDAL, Eur.Phys.J.C 82 (2022) 694

HECOs results

- Limits on HECOs with electric charges in the range **15*e* – 175*e*** and masses from **110 – 1020 GeV**
- Upper limits on production cross section **~ 30–70 pb**
- Better sensitivity expected in ongoing **Run 2 analysis**
  - higher c.m.s. energy: 13 TeV
  - larger integrated luminosity
  - larger exposed NTD surface
  - lower CR39 *Z/β* threshold than Macrofol

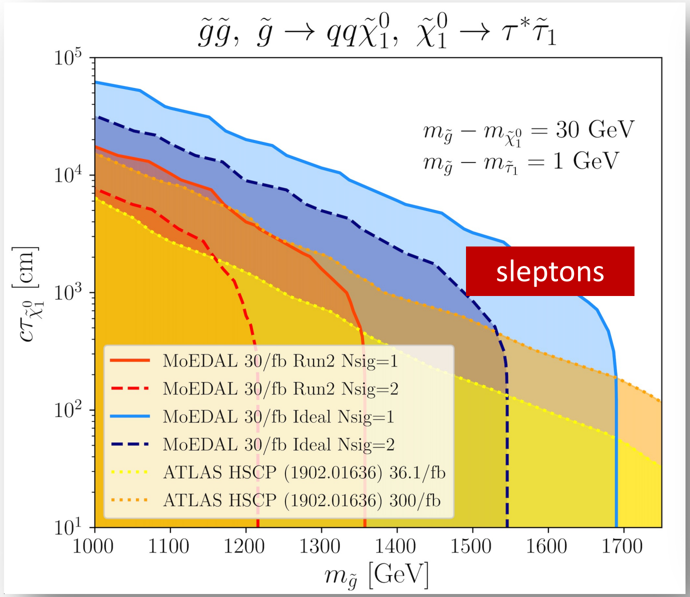


Non-perturbativity of large coupling can be tackled by appropriate **resummation**
[Alexandre, Mavromatos, Musumeci, VAM, *LHCP2023 & paper in preparation*]

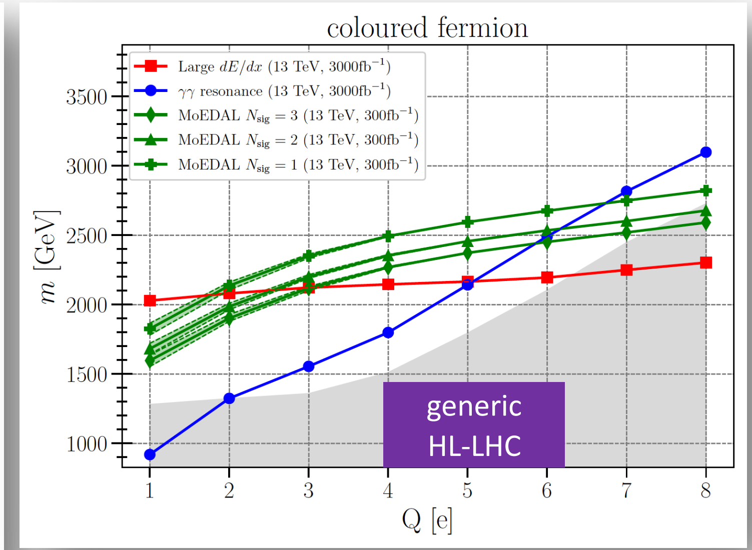
MoEDAL HECOs limits are the strongest to date, in terms of charge, at any collider experiment

"Low" electric charges

- Supersymmetric singly charged LLPs: sleptons, R-hadrons, charginos
- **Generic multiply charged particles**
- Also, models of ν masses → 2-, 3-, 4-ply charged [Hirsch et al, EPJC 81 (2021) 697]



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

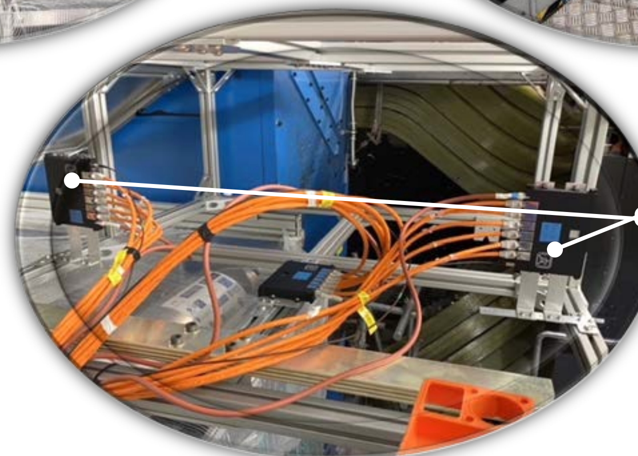


Altakach, Lamba, Masełek, VAM, Sakurai, EPJC 82 (2022) 848

MoEDAL has the best sensitivity at intermediate electric charges at HL-LHC

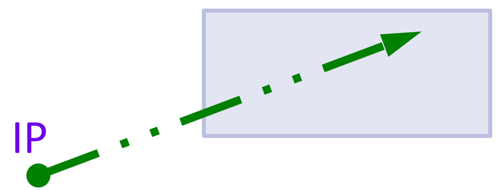
Upgraded MoEDAL installed for Run-3

- Upgrades to Run-2 MoEDAL
- Completed in March 2023

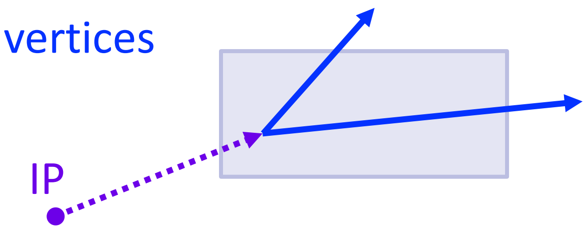


MAPP – MoEDAL Apparatus for Penetrating Particles

MAPP-mQP: sensitive to low ionisation induced by *millicharged* particles (**mCPs**), i.e. particles with charges ≪ 1*e*



MAPP-LLP: sensitive to very long-lived weakly interacting neutral particles through visible decay products → displaced vertices



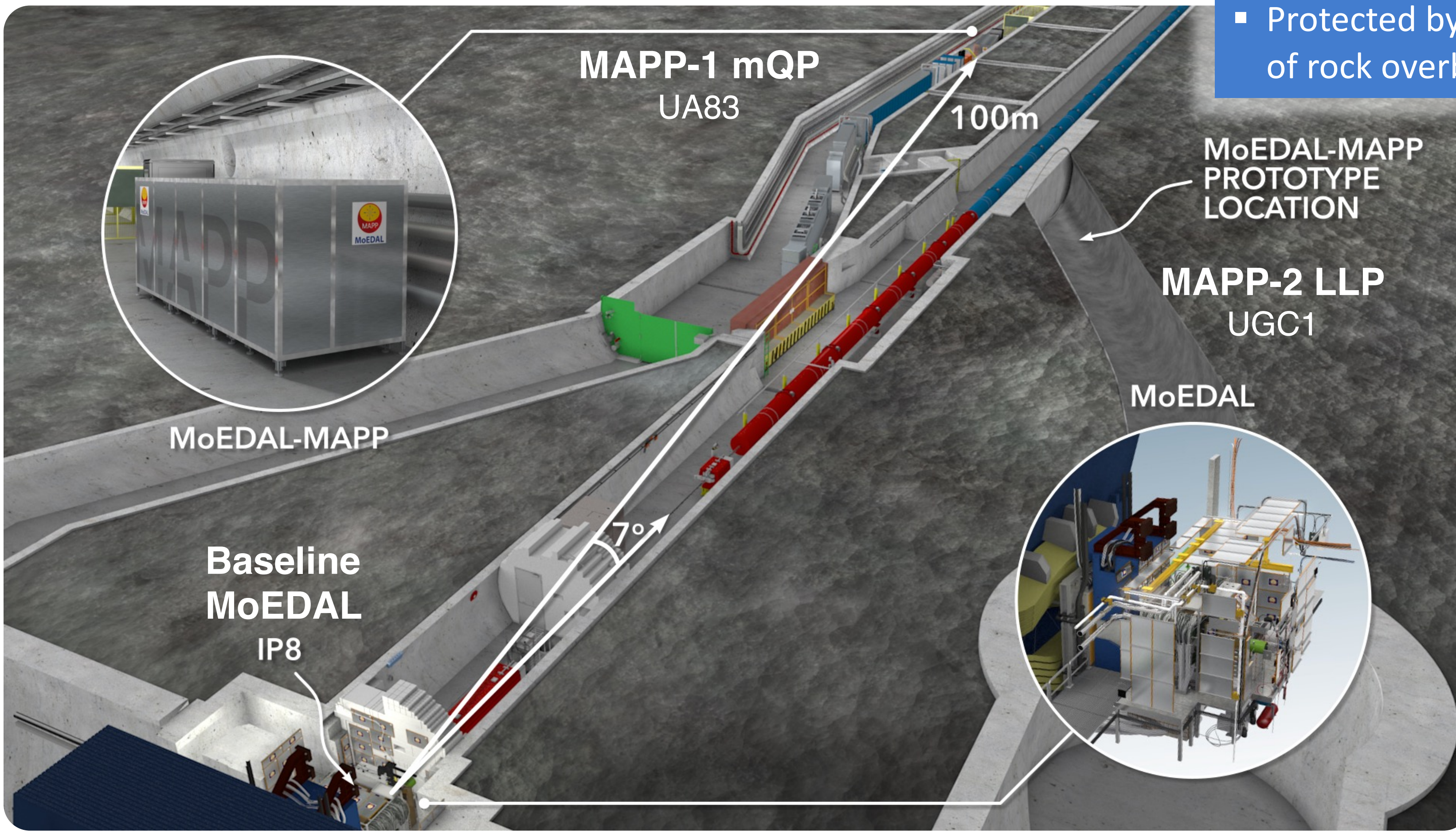
- Phase-1 ***approved*** *by CERN Research Board* in 2021
- **Phase-1** for **Run-3** (2022–2025): **MAPP-mQP** installation in UA83 is underway
- **Phase-2 HL-LHC** (2029 –): Reinstall Phase-1 in UA83 and add **MAPP-LLP** in UGC1

MoEDAL-MAPP flythrough:
http://www.physixel.com/JLP_MAPP/MAPP_FlyOver1.mp4

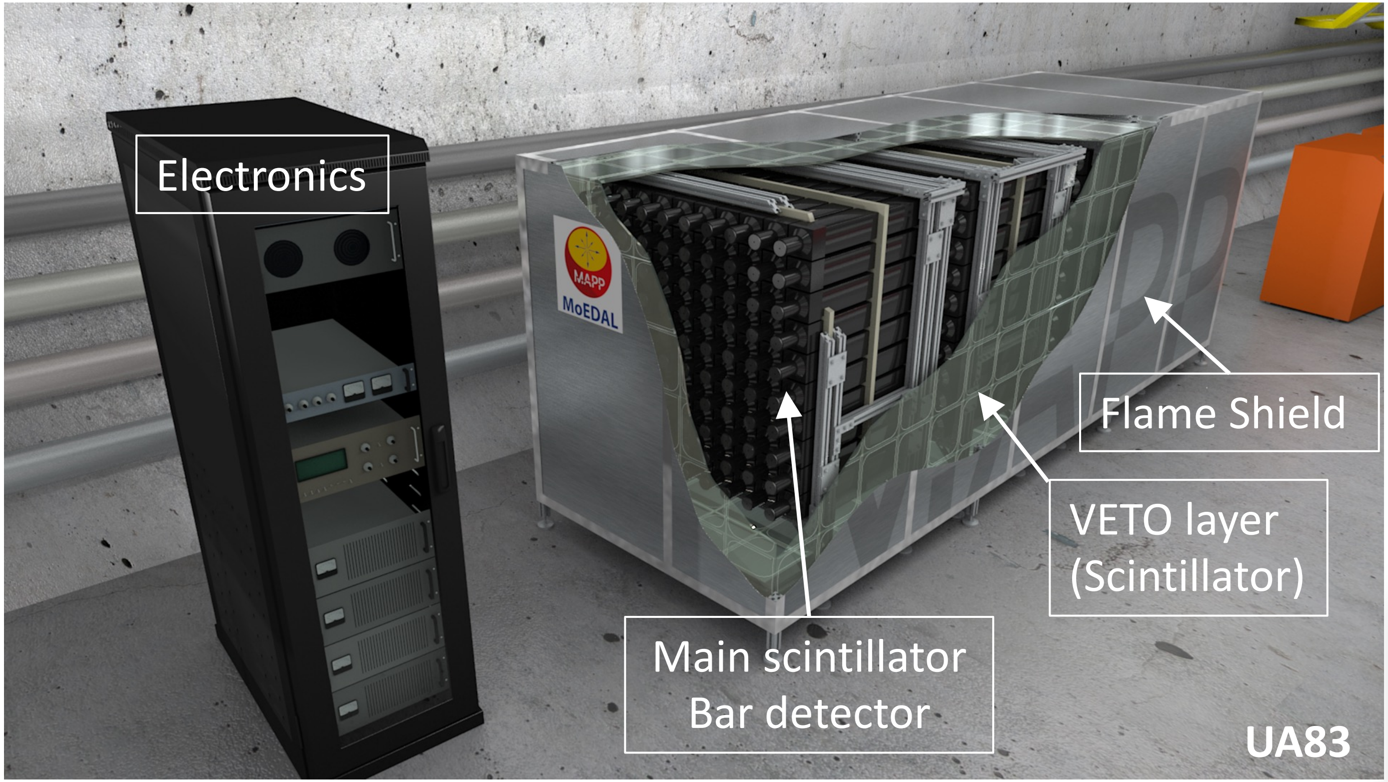
Pinfold, Phil.Trans.Roy.Soc.Lond.A 377 (2019) 20190382

MAPP locations

- At forward region w.r.t. beam axis
- Protected by ~100 m of rock overburden



MAPP-mQP Phase-1 detector concept



- 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

Prototype mQP in 2017 in UGC1 gallery

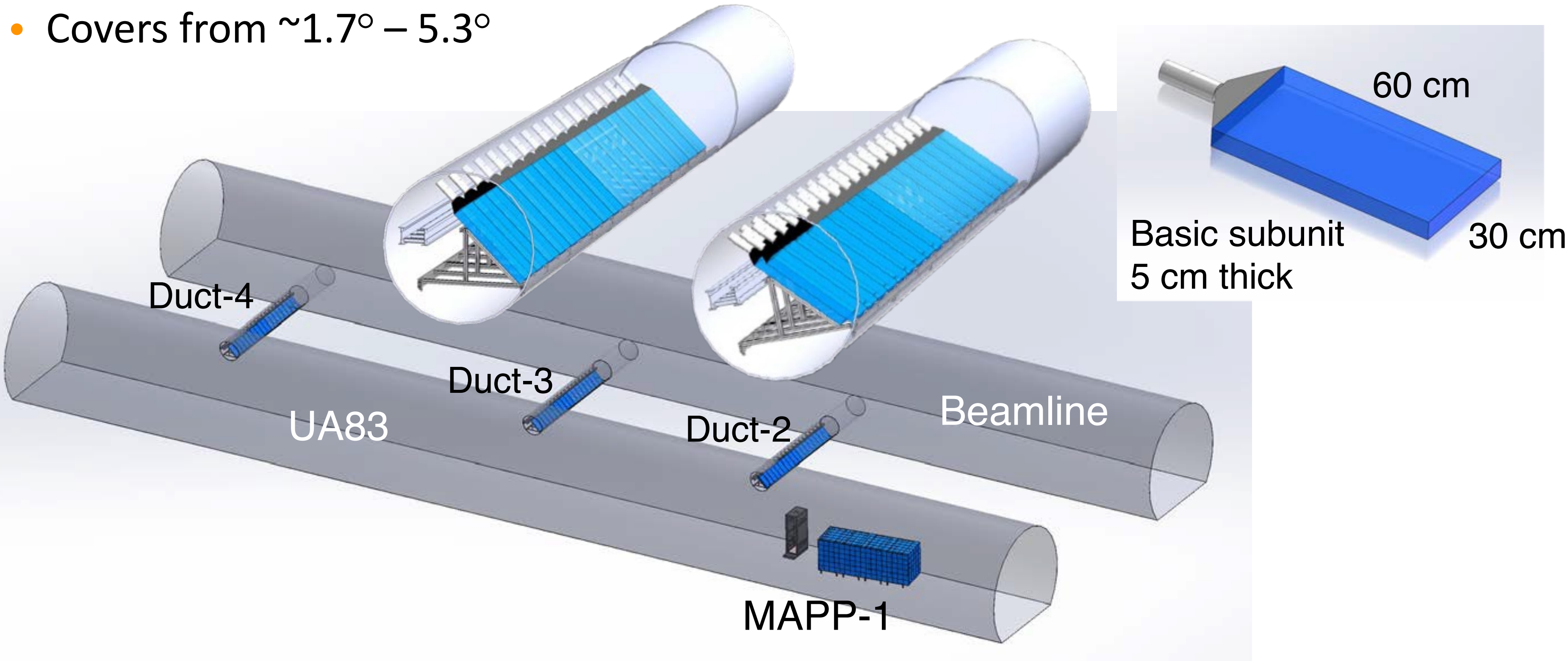
MAPP-mQP Phase-1 installation

UA83, March 2023

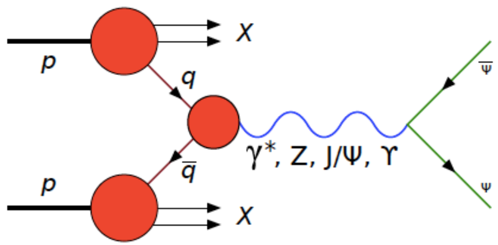
- Installation continues through June 2023
- Data taking expected to start later in 2023

MAPP-1 Outrigger Detector

- To increase the acceptance of MAPP-1 at higher mass & larger fractional charge
- Size of the scintillator “planks” 6m × 0.6m × 5cm, inclined at 45°
- Covers from ~1.7° – 5.3°

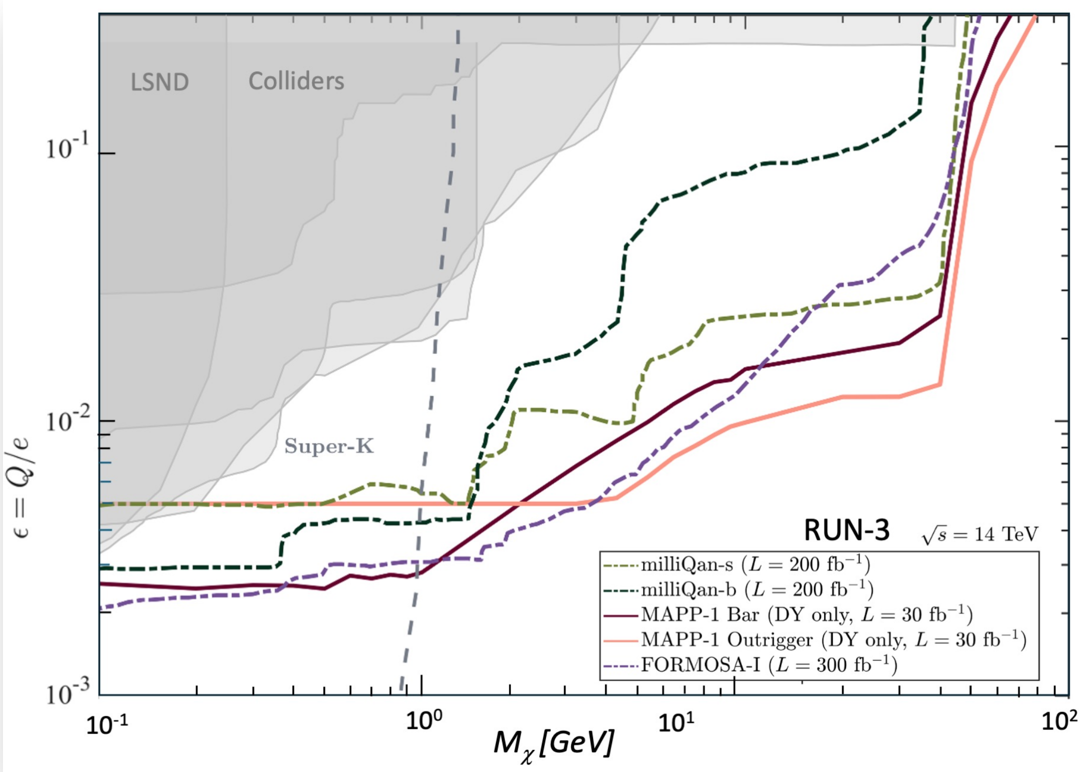


Millicharged particles



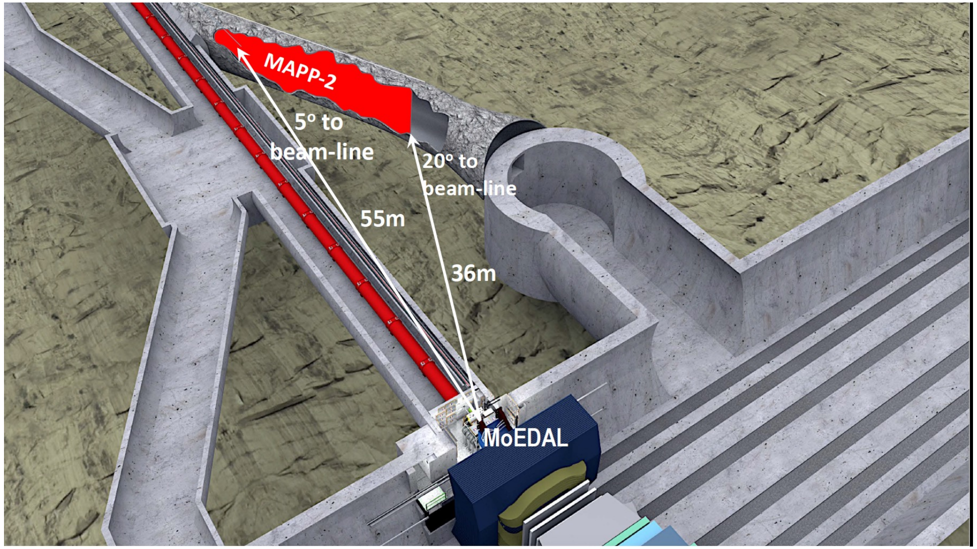
- mCP generated by **massless dark photon**, kinetically mixed with SM, that couples to millicharged χ
- MAPP sensitive to **heavy neutrino** with large **electric dipole moment**, experimentally similar to mCP [Frank et al, Phys.Lett.B 802 (2020) 135204]

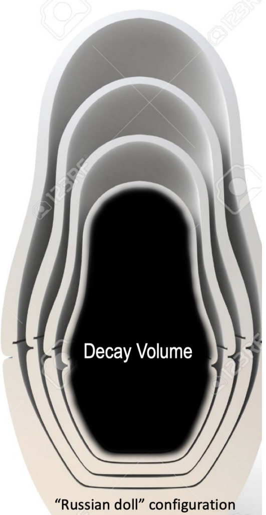
MoEDAL contribution to Snowmass, arXiv:2209.03988



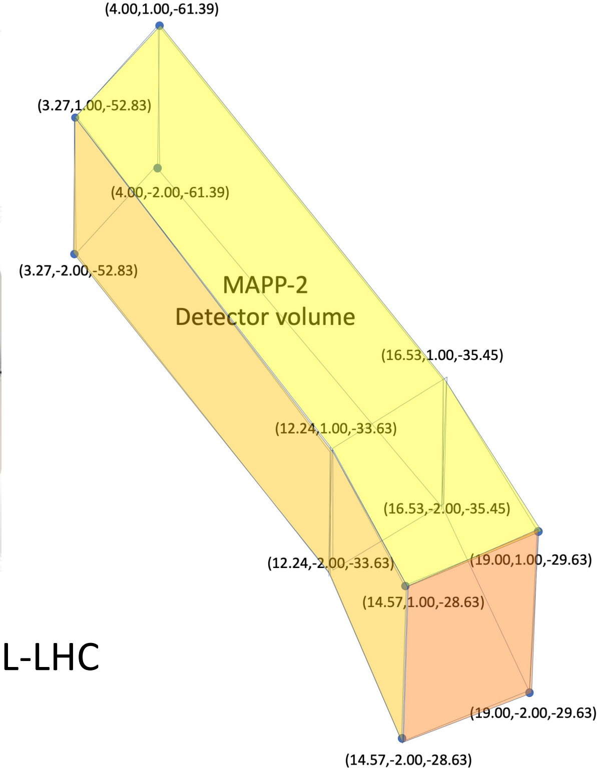
MAPP-1: DY only, 100% eff., no background
milliQan: DY+meson decays, bkg.+detector eff. included
FORMOSA-1: DY+meson decays, 100% eff., no background

Phase-2: MAPP-2 upgrade for HL-LHC





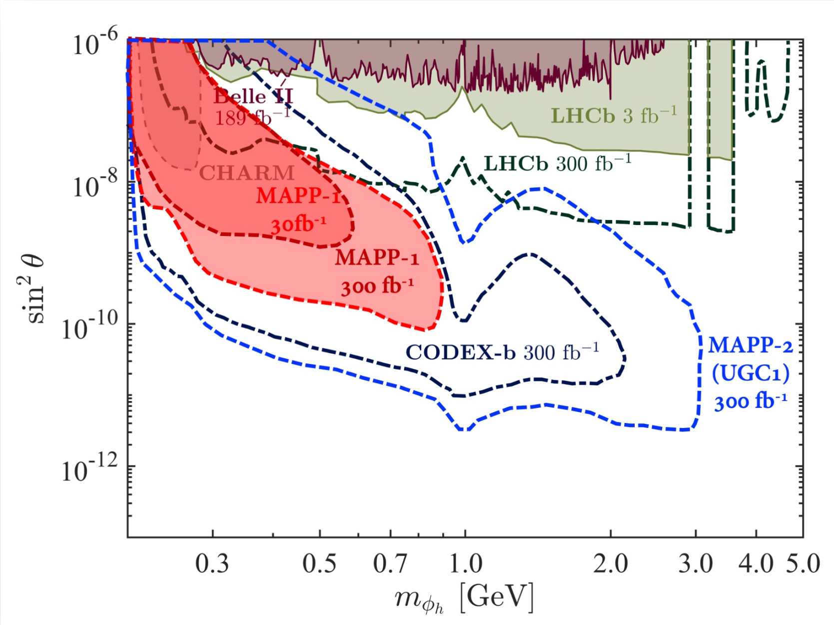
"Russian doll" configuration of scintillator walled boxes



- The UGC1 gallery will be prepared during Long Shutdown 3 prior to HL-LHC
- MAPP-2 detector extends to the full length of the UGC1 gallery
- Detector technology: large scintillator tiles with optical-fibre readout
- Tracking detectors formed by 3 or 4 hermetic containers – one within the other – lining UGC1 walls

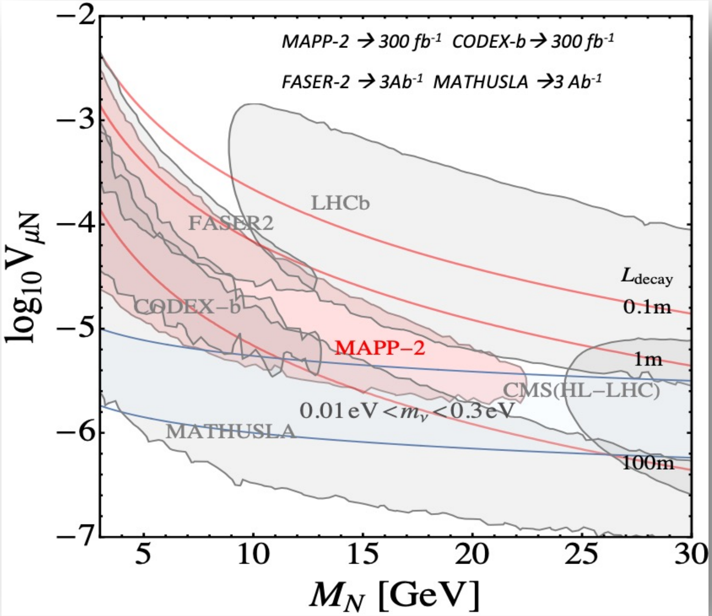
MAPP – dark matter & heavy neutrinos

Dark Higgs scenario



Dark Higgs ϕ mixes with SM H^0 (mixing angle $\vartheta \ll 1$), leading to exotic $B \to X_s\phi$ decays with $\phi \to \ell^+\ell^-$

Heavy neutrino via *Z'* production

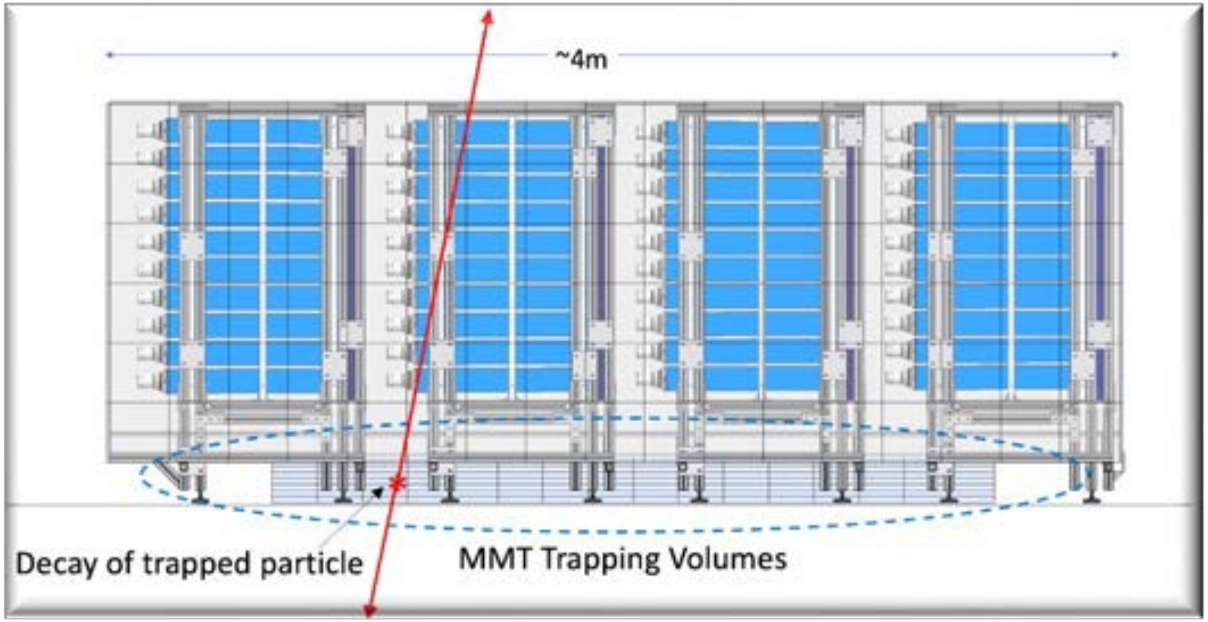


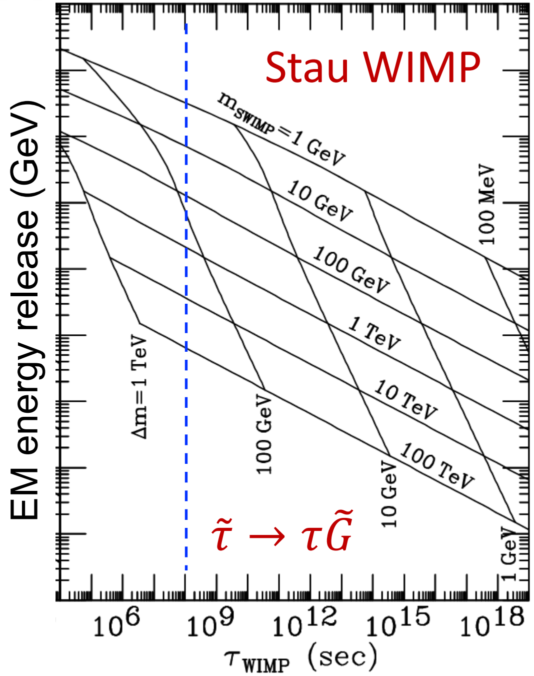
Pair production of RH neutrinos from the decay of a *Z´* boson in the gauged *B-L* model

MoEDAL contribution to Snowmass, arXiv:2209.03988

Probing extremely long-lived particles

- After exposure and SQUID scan, MMTs will be monitored for decaying *electrically charged* particles possibly **trapped** in their volume
- Sensitive to e, μ, γ, hadrons with energy as small as 1~GeV
- Estimated probed lifetimes ≳ **1 yr**





- SuperWIMP model for cold dark matter
- WIMP → SM + SWIMP

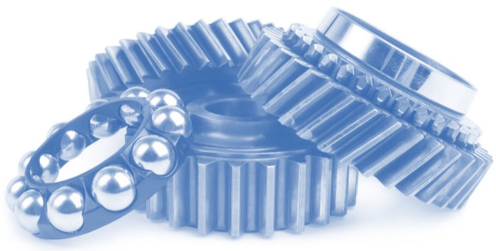
Feng, Rajaraman, Takayama, Phys. Rev. D 68, 063504 (2003)

Summary & outlook

- Exciting results by MoEDAL
  - sole contender in **high magnetic charges**
  - sole **dyon** search in accelerator experiment
  - first search for monopoles produced via **Schwinger mechanism**
  - entered the arena of ***electrically* charged particles**
- Upcoming results
  - CMS beam pipe analysis ➜ constrain very high magnetic charges
  - Second NTD analysis ➜ improved sensitivity to electric charges
- **Future perspectives**
  - MoEDAL baseline redeployed for **Run-3** with improved geometry
    - 5 times higher instantaneous luminosity than Run-2
    - also planned to operate during **HL-LHC**
  - MAPP will extend reach to **millicharged** particles and **neutral long-lived particles**
    - Phase-1 MAPP installation ongoing; expected to start data-taking in 2023
    - best sensitivity for neutral LLPs in Run-3 among planned experiments

MoEDAL web page:
https://moedal.web.cern.ch/

Spares



MoEDAL – Monopole & Exotics Detector At LHC

Optimised for anomalously ionising (meta)stable particles

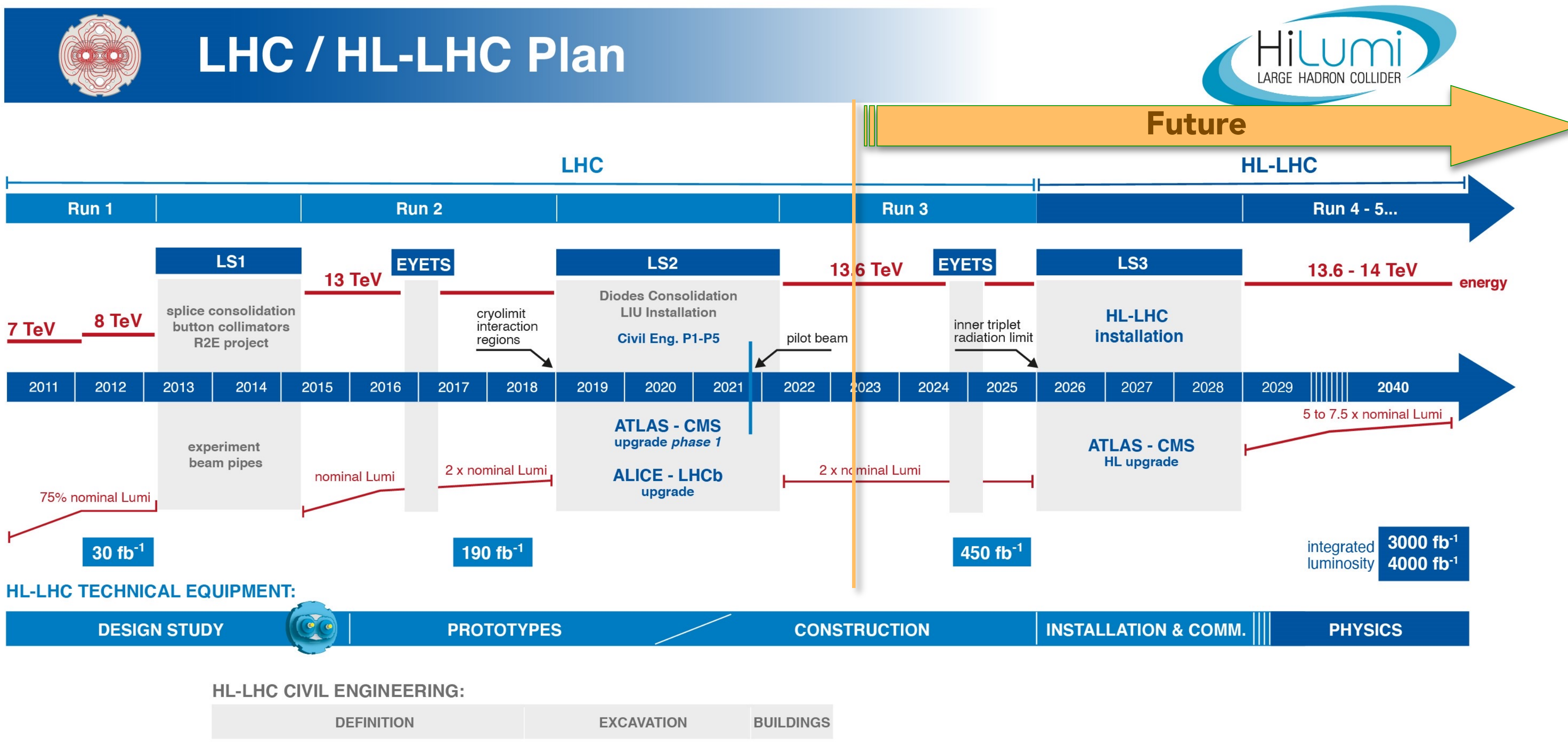
MAPP
MoEDAL

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

Results

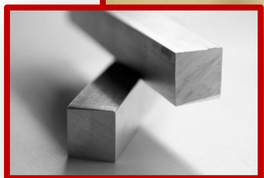
- 2016 – **First monopole results @ 8 TeV** ☛ *CERN Press Release*
  JHEP 1608 (2016) 067 [arXiv:1604.06645]
- 2017 – **First monopole results @ 13 TeV** Phys.Rev.Lett. 118 (2017) 061801 [arXiv:1611.06817]
- 2018 – **MMT results** Phys.Lett.B 782 (2018) 510–516 [arXiv:1712.09849]
  - **spin-1 monopoles ← FIRST in colliders**
  - β-dependent coupling
- 2019 – **MMT results** Phys.Rev.Lett. 123 (2019) 021802 [arXiv:1903.08491]
  - **photon fusion** interpretation **← FIRST at LHC**
- 2020 – **MMT search for Dyons ← FIRST in colliders**
  Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]
- 2021 – **Schwinger thermal production ← FIRST**
  Nature 602 (2022) 7895, 63 [arXiv:2106.11933]
- 2021 – **NTD & MMT ← FIRST NTD analysis** arXiv:2112.05806
  - First limits in highly electrically charged objects

LHC & High Luminosity LHC (HL-LHC)



Run-2 MoEDAL deployment

MMT
- Installed in forward region under beam pipe & in **sides**
- Approximately **800 kg** of Al
- Total 2400 aluminum bars



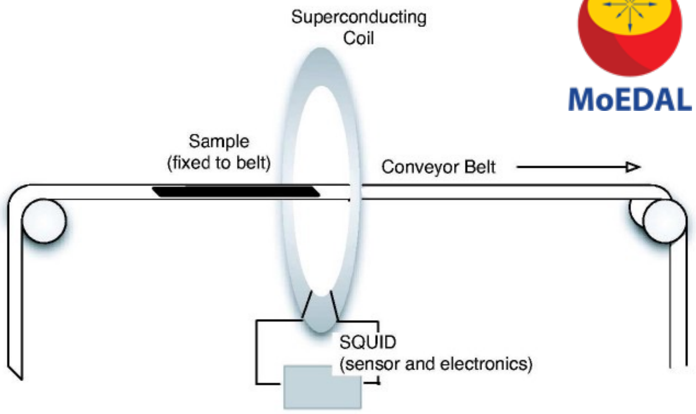
Low-threshold NTD
- Top of VELO cover
- Closest possible location to IP

HCC-NTD
Installed in LHCb acceptance between RICH1 and Trigger Tracker

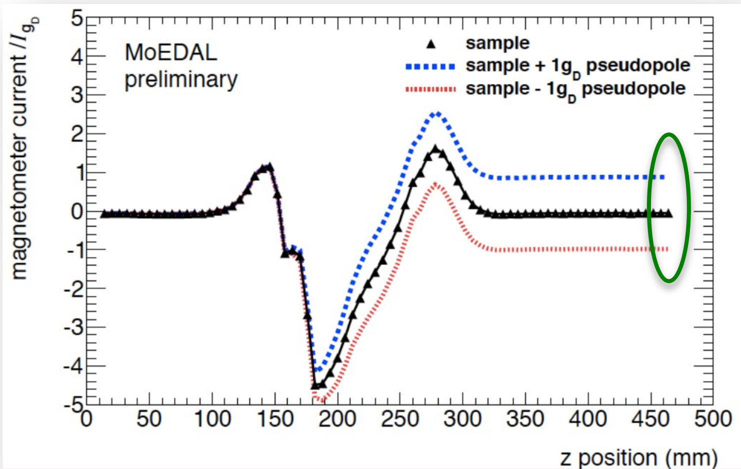
MoEDAL

MMT scanning

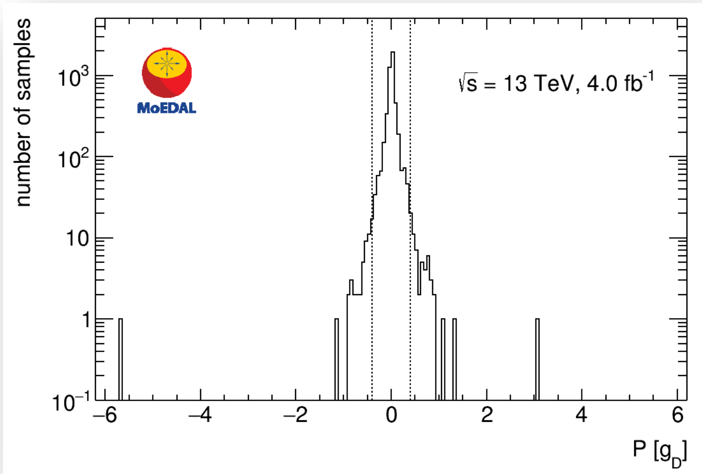
- Monopoles can bind to nuclei and get trapped
- MMTs analysed in superconducting quantum interference device (SQUID) at ETH Zurich
- **Persistent current:** difference between resulting current after and before
- Outliers are **scanned several times** further



SQUID analysis – Persistent current after first two passages for all samples

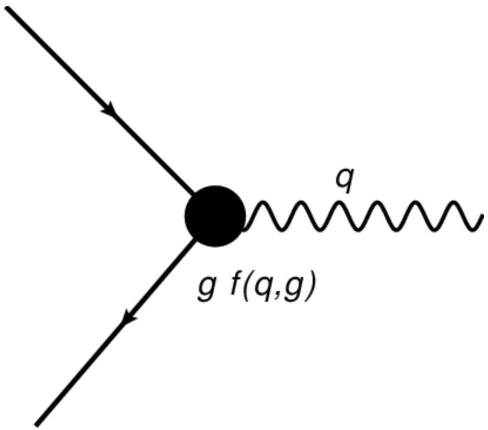


Calibration: Typical sample & pseudo-monopole curves



MoEDAL, PRL 123 (2019) 021802

Magnetic monopoles in a nutshell



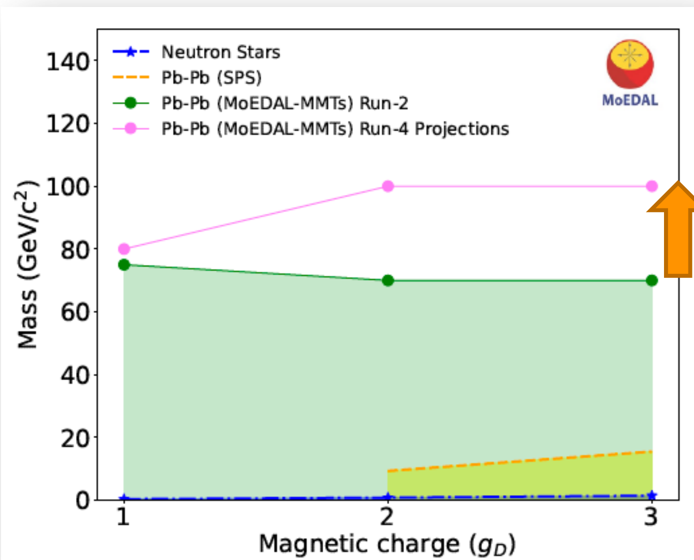
- Why? Because they symmetrise Maxwell's equations
  - electric ↔ magnetic charge duality
- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges are integer multiples of Dirac charge: $g = ng_D$, $n = 1, 2, \ldots$
  - if carries electric charge as well, is called **Dyon**
- Photon-monopole coupling constant
  - large: $g/\hbar c \sim 20$ (precise value depends on units)
- Dirac monopole is a *point-like* particle; GUT monopoles are *extended* objects
  - production of composite monopoles exponentially suppressed by $e^{-4/\alpha}$
- Monopole spin & mass is not determined by theory → free parameters

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

Monopoles in Schwinger mechanism – Future

MoEDAL

- **Run-1 CMS beam pipe analysis in heavy-ion run**
- HL-LHC projection for MoEDAL's MMTs
  - Conservative theoretical assumptions
  - Nuclear track detectors not included in projection
  - Assuming 2.5 nb^{-1} Pb-Pb collisions at $\sqrt{s_{NN}} = 5.52$ TeV



~20 GeV increase in sensitivity in HL-LHC heavy-ion run

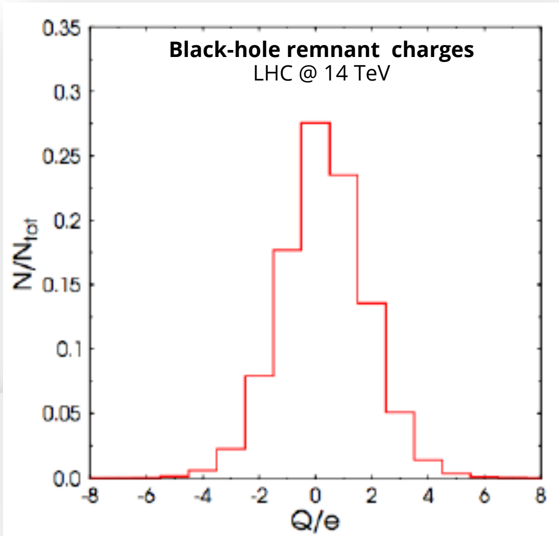
Opportunities for new physics searches with heavy ions at colliders, Snowmass 2021 white paper, arXiv:2203.05939

For FCC : $\sqrt{s_{NN}} \sim 40$ TeV
$\Rightarrow M \gtrsim 600$ GeV

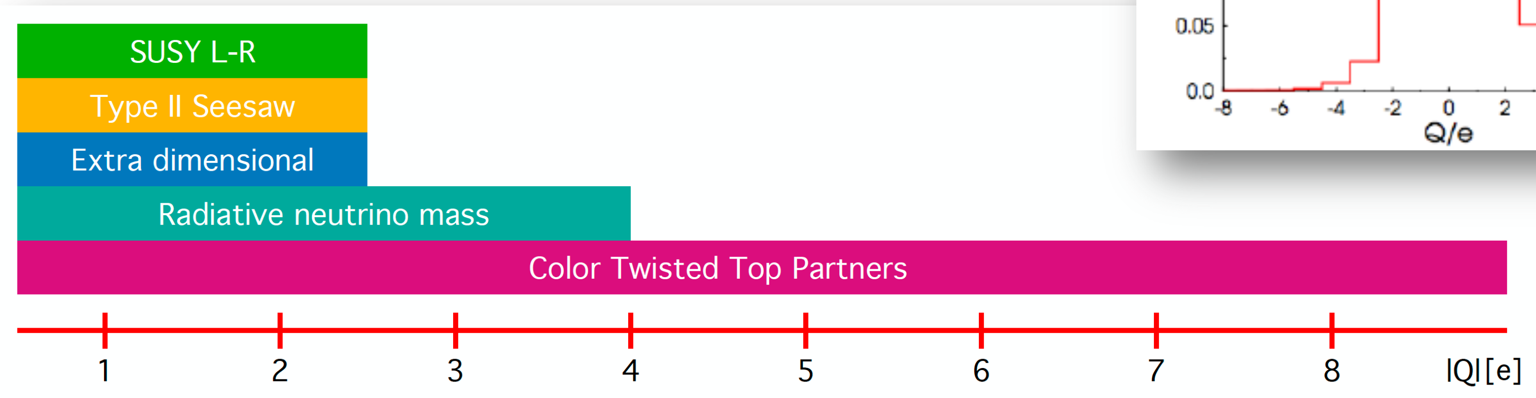
Theoretical improvements in semiclassical and fully classical approaches

Multiply charged quasi-stable particles

- Highly Electrically Charged Objects (HECOs) predicted in many scenarios of physics beyond the SM
  - finite-sized objects (Q-balls)
  - condensed states (strangelets)
  - microscopic black holes (through their remnants)
  - …
- They eventually decay into other particles
- Detected by **high ionisation**



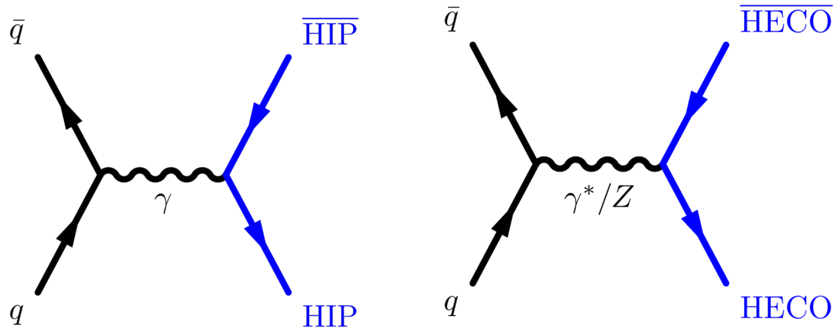
Hossenfelder, Koch, Bleicher, hep-ph/0507140



R. Masełek, DISCRETE2020-2021

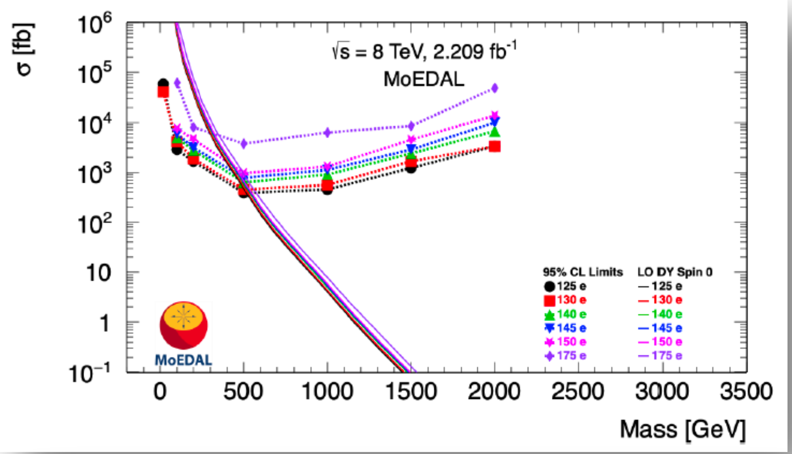
NTD results on HECOs

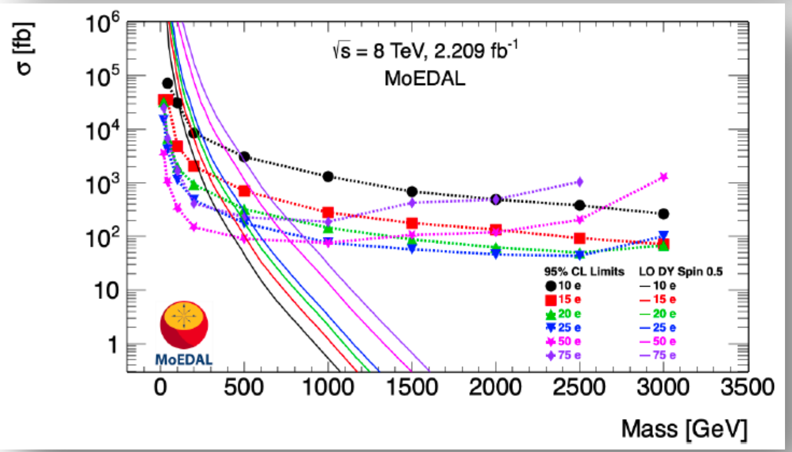
- Drell-Yan production
  - *Z* exchange is also taken into account for fermions [Song & Taylor, J.Phys.G 49 (2022) 045002]



  - non-perturbativity of large coupling can be tackled by appropriate **resummation** [Alexandre, Mavromatos, Musumeci, VAM, *in progress*]
- Limits set on HECO pair production with cross section **~ 30 – 70 pb**

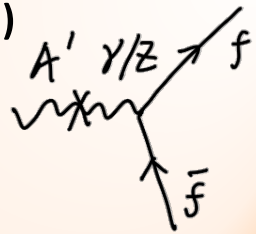
MoEDAL, EPJC 82 (2022) 694



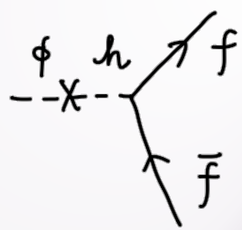


Hidden sector – Feebly Interacting Particles (FIPs)

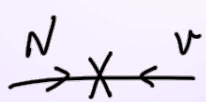
Dark vectors (“Dark Photons”)
- adding U(1) gauge group to SM, kinetic mixing with γ/Z
- light neutral meson decays, millicharged particles



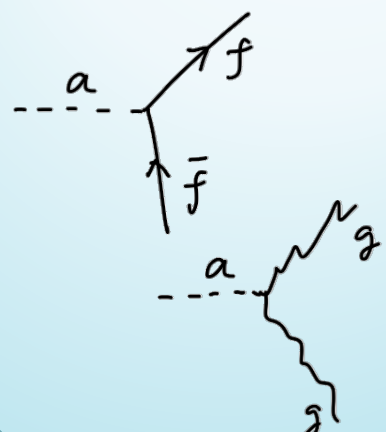
Dark scalars (“Dark Higgs”)
- neutral singlet scalers that couple to the SM Higgs field
- produced in penguin decays of K, D, B mesons

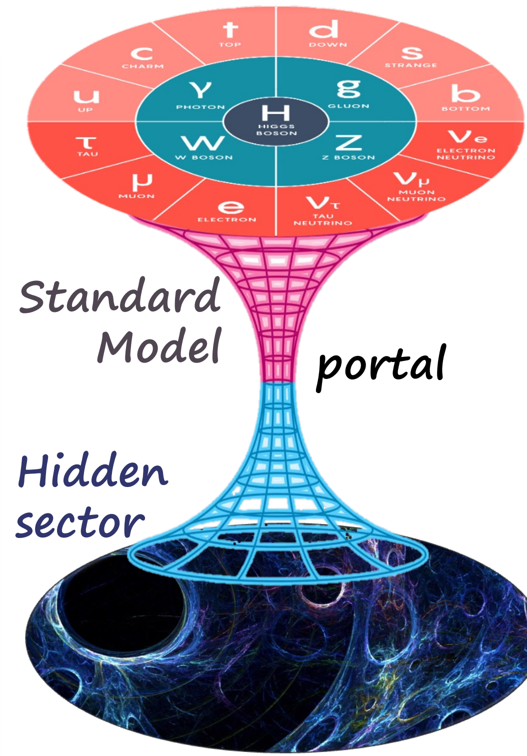


Heavy neutral leptons (“sterile neutrinos”)
- explain SM ν masses (seesaw), DM, BAU
- weak semi-leptonic decays of hadrons, W, Z



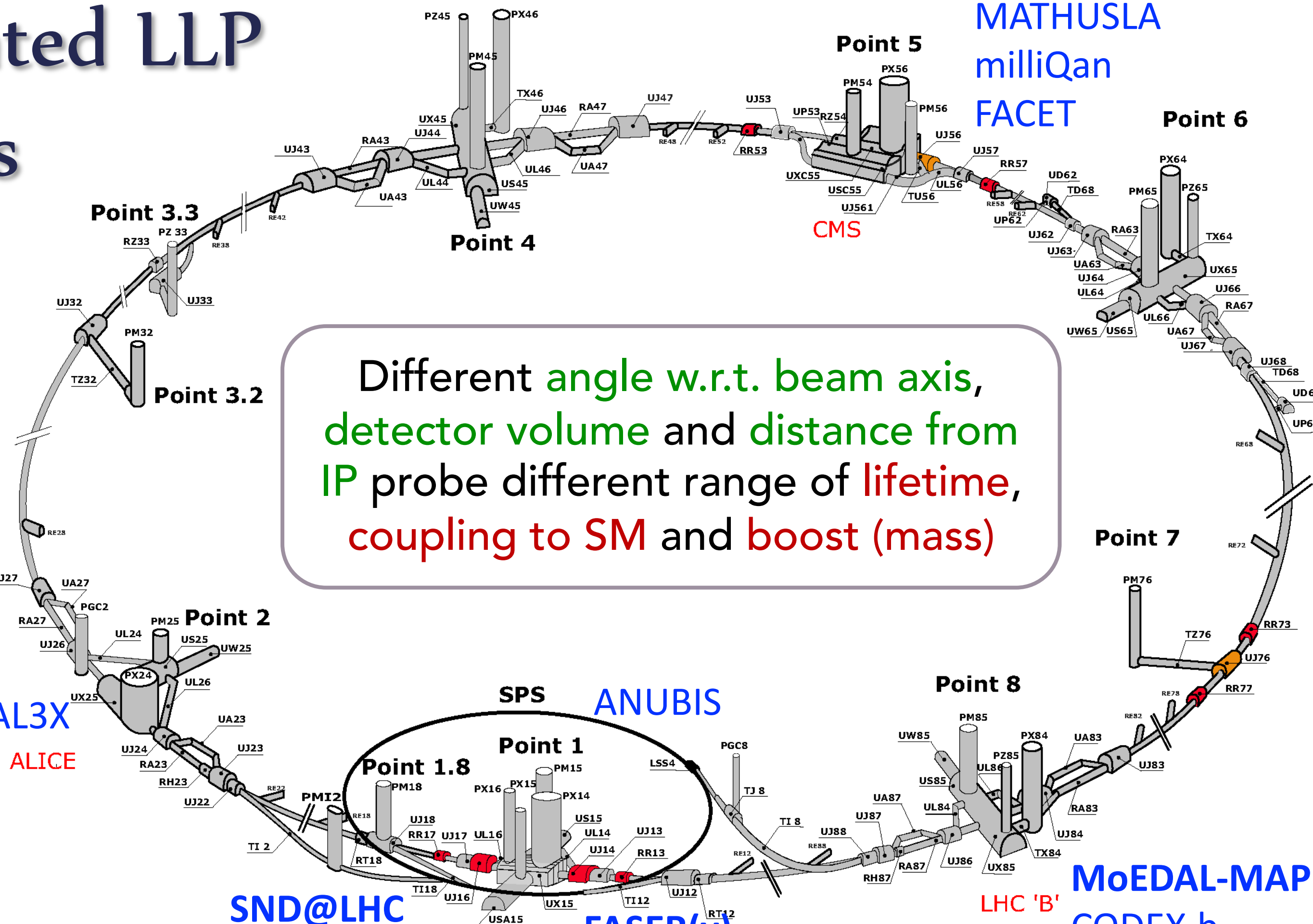
Axion-like particles (“ALPs”)
- solution of the strong CP problem
- generalisation of the axion model in MeV-GeV mass range





For a review on LLP experiments, see: VAM, MG16 procs. arXiv:2111.03036

LHC dedicated LLP experiments



MATHUSLA
milliQan
FACET

AL3X

ANUBIS

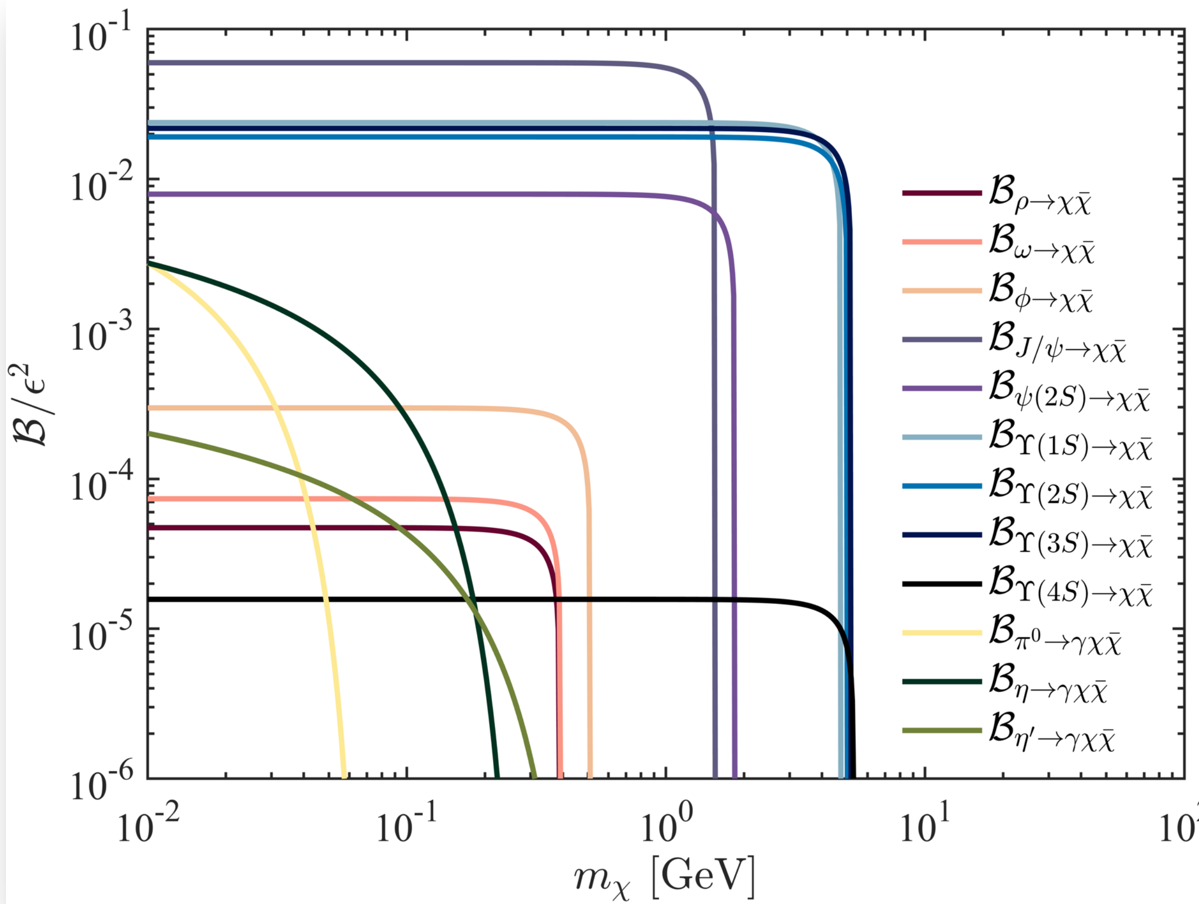
SND@LHC

FASER(ν)
FORMOSA

MoEDAL-MAPP
CODEX-b

Different angle w.r.t. beam axis, detector volume and distance from IP probe different range of lifetime, coupling to SM and boost (mass)

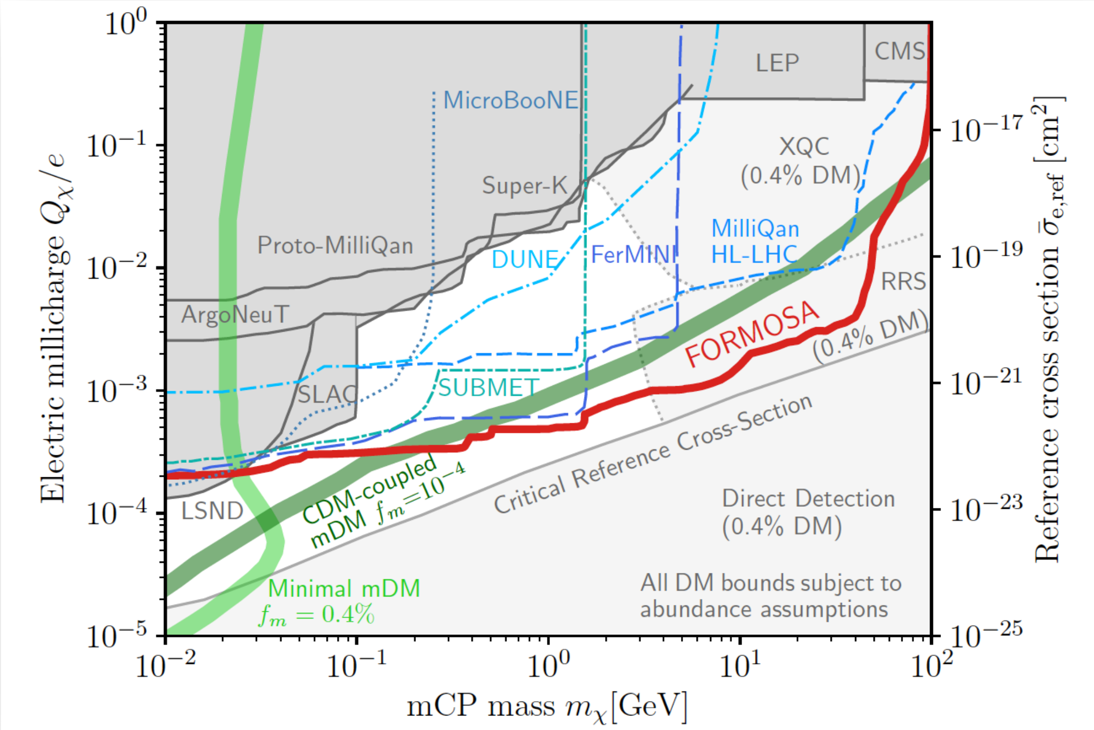
Meson decays to MCPs



MoEDAL contribution to Snowmass, arXiv:2209.03988

Millicharged strongly interacting DM (mSIDM)

- mCPs can account for a fraction of dark matter abundance
- mSIDM characterised by a large "reference cross section"
- Particle flux attenuated through interactions in the Earth's atmosphere and crust
- Can escape detection by conventional underground direct-detection detectors
- FORMOSA can help close the mSIDM window



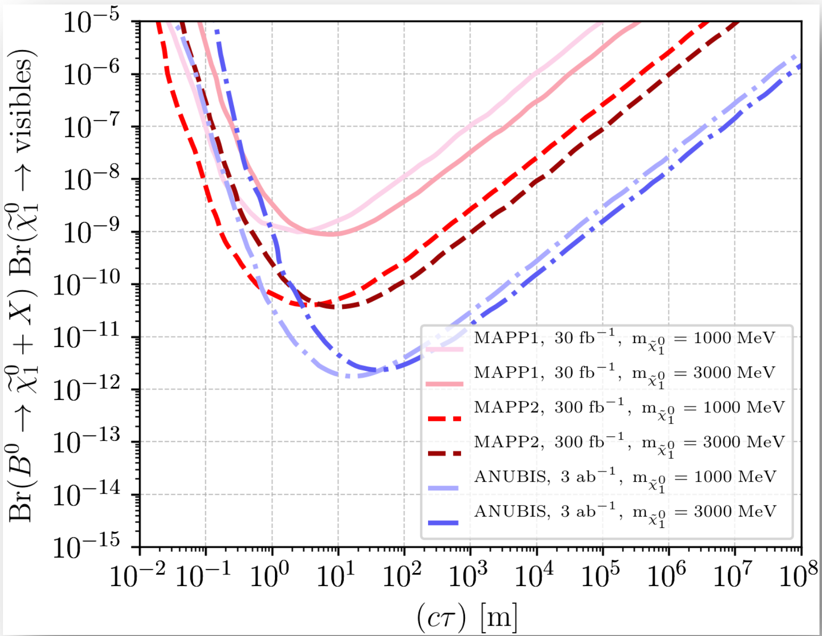
Emken, Essig, Kouvaris, Sholapurkar, JCAP 09 (2019) 070
Foroughi-Abari, Kling, Tsai, PRD 104 (2021) 035014

FPF Paper Phys.Rept. 968 (2022) 1

FORMOSA: Scintillator-based detector

R-parity violating supersymmetry

If RPV coupling, λ, λ’, λ’’ small enough, the (N)LSP may be long lived



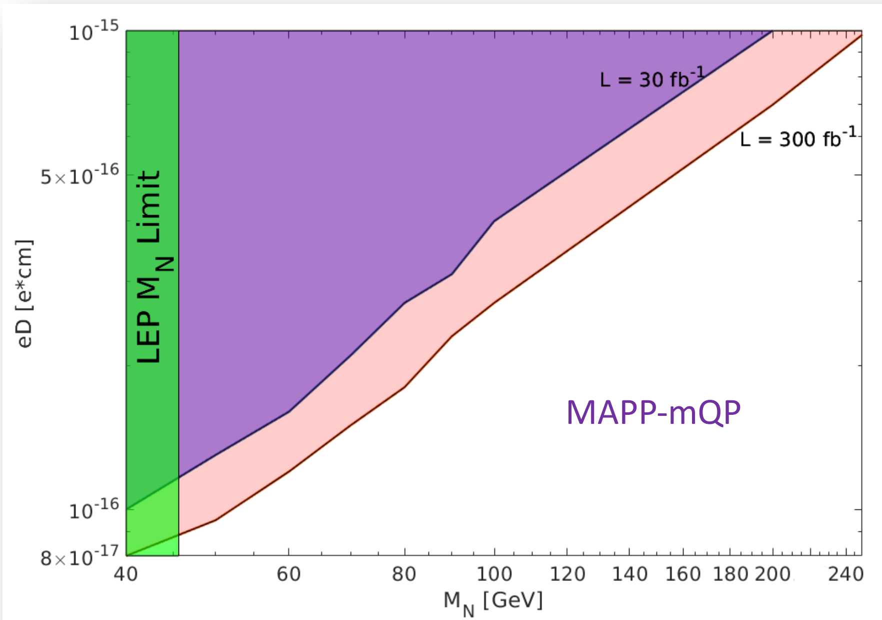
Dreiner, Günther, Wang,
PRD 103 (2021) 075013

$\tilde{\chi}_1^0 \to$ charged

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

RPV couplings

mCPs – Heavy neutrino with large EDM



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

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

Axion-like particles (ALPs)

- ALPs produced via rare decays of π and η mesons
- Light ALPs with mass of 10 MeV – 1 GeV with suppressed couplings can be long lived
- They can be detected in MAPP-LLP

95% CL for ALPs @ √s = 14 Tev