Overview of ATLAS BSM and MoEDAL

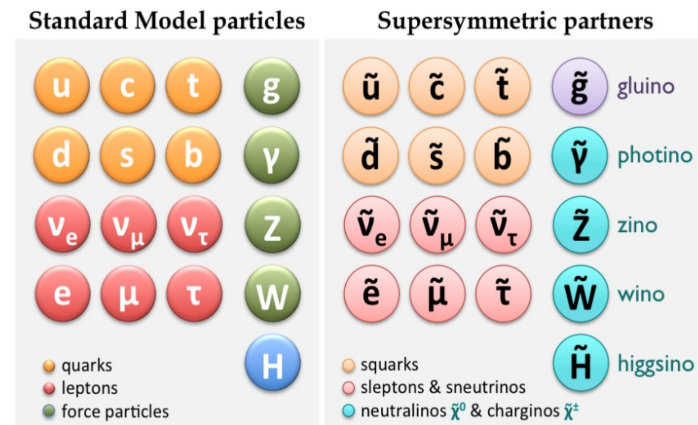
Vasiliki A. Mitsou

AITANA Annual Meeting 2023/2024 – Matter & Technology
1–2 February 2024, IFIC

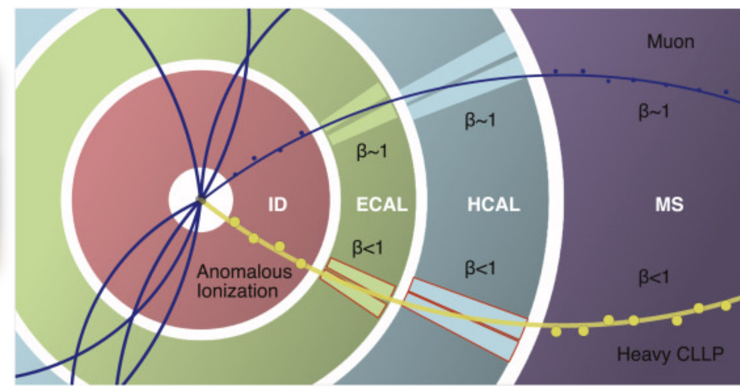
ATLAS searches for physics beyond the Standard Model

Supersymmetry (SUSY)

- Global symmetry between fermions & bosons
- Predicts a **Higgs** scalar compatible with observed one
- Unification of gauge couplings at a single scale
- **Dark matter** candidate



AITANA contributions to least explored, unconventional signatures
- *R-parity violation (RPV)*
- *Long-lived particles (LLPs)*



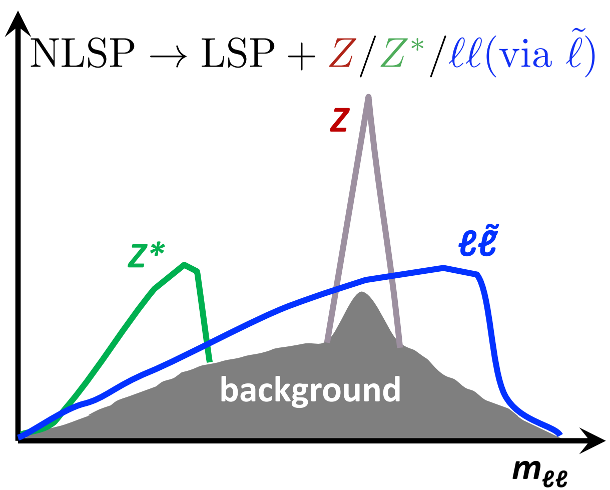
$$W_{\not{R}p} = \underbrace{\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k^C + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k^C + \underbrace{\epsilon_i\hat{L}_i\hat{H}_u}_{\text{bilinear terms}}}_{L\text{-number violation}} + \underbrace{\lambda''_{ijk}\hat{U}_i^C\hat{D}_j^C\hat{D}_k^C}_{B\text{-number violation}}$$

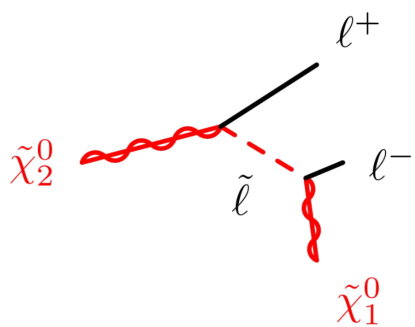
for a review, see: VAM, PoS(CORFU2022)074

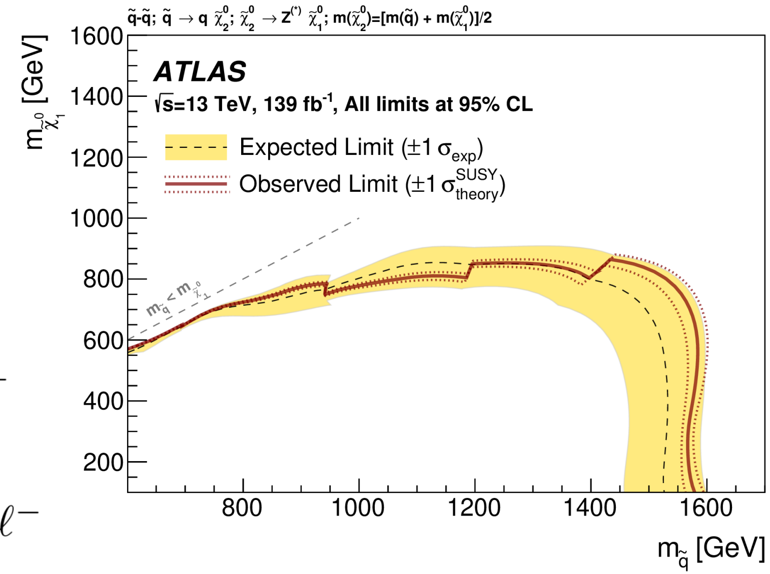
Peak or edge in $m_{\ell\ell}$ distribution

[Eur.Phys.J.C 83 (2023) 515]

- Full final-state reconstruction impossible due to "invisible" lightest SUSY particles (LSPs)
- Two opposite-sign same-flavour leptons: $\boldsymbol{m_{\ell\ell}}$ distribution better handle than tails
- Exclude SUSY mass parameter space by "stitching" signal regions
- First analysis with **electroweak production**







Shape fit studies in Cabrera, VAM et al, [JHEP 04 (2012) 133]

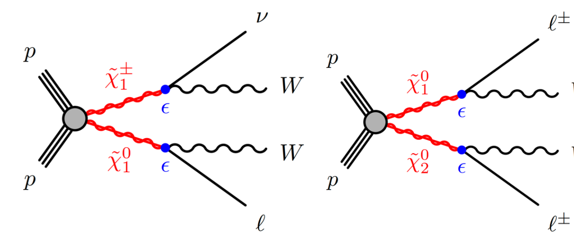
Previous IFIC contributions:
[EPJC 78 (2018) 625], [EPJC 77 (2017) 144], [EPJC 75 (2015) 318]

Two same-sign leptons

[JHEP 11 (2023) 150]

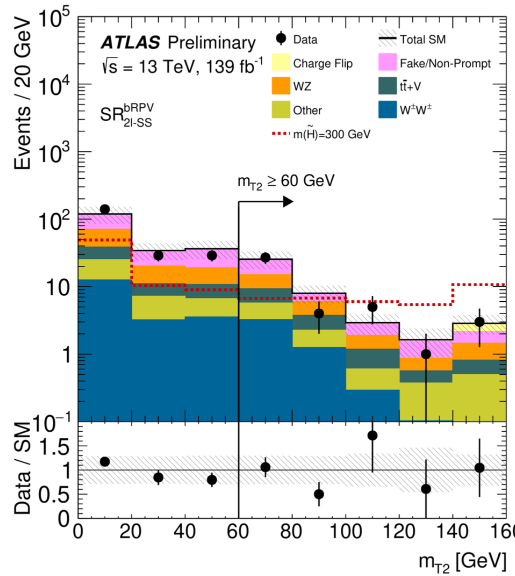
***AITANA contributions**: bRPV analysis, paper editor & contact editor*

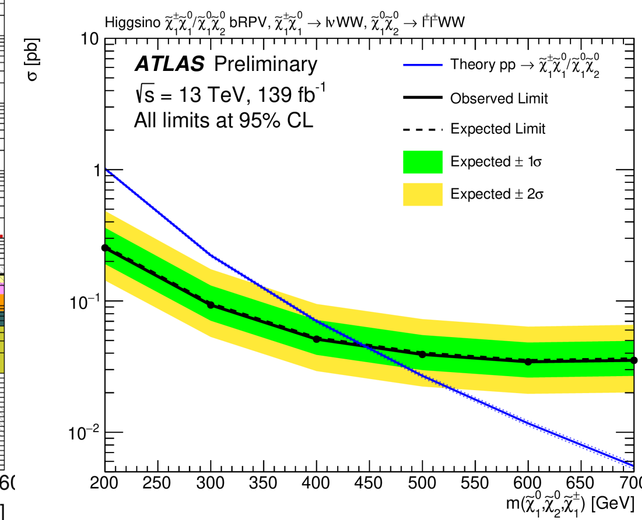
- Advantage: Small SM same-sign leptonic backgrounds
- Sensitivity to both R-parity conserving and RPV SUSY
- Near-degenerate **higgsino** spectra favoured by **naturalness**, *without* soft leptons in final state thanks to RPV decays of LSPs



Bilinear RPV (bRPV)

- bRPV terms induce **neutrino masses**
- inclusive higgsino production
- **first analysis for this scenario**

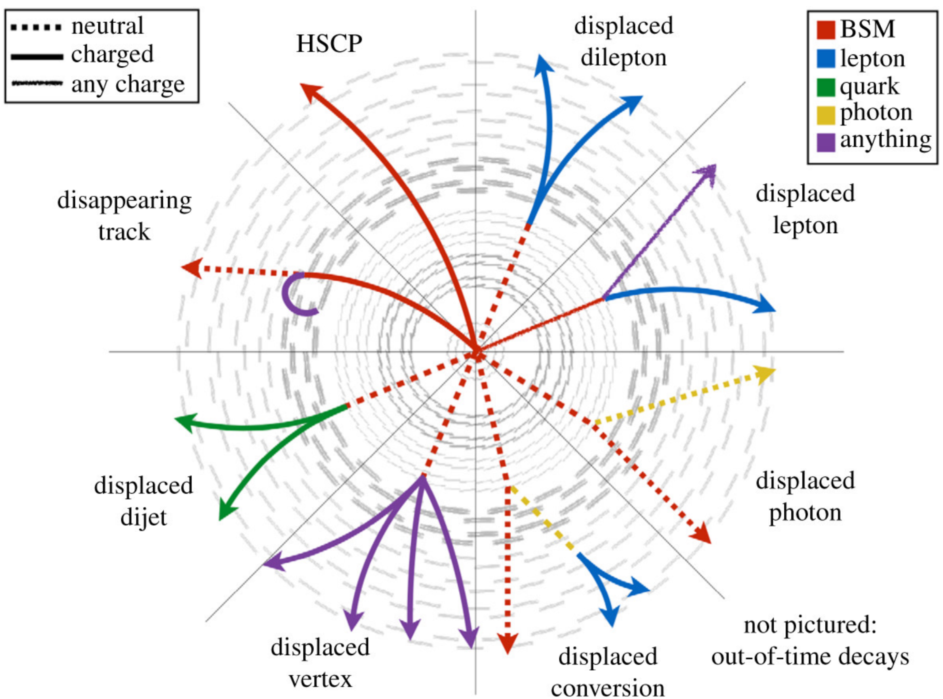




IFIC has led bRPV analyses at LHC
PRD85(2012)012006, PRD86(2012)092002, ATLAS-CONF-2012-140, JHEP09(2014)103, JHEP06(2014)035, JHEP04(2015)116, JHEP10(2015)054, ATLAS-CONF-2015-018,
PhD theses: Emma Torró, Elena Romero

Current analysis and future plans

- Search for Stable Massive Particles [ANA-SUSY-2019-03]
  - Long-lived staus (SUSY partners of taus)
  - Energy loss and velocity information from muon spectrometer
  - In collaboration with Univ. Athens & Univ. Aegean
  - Status: EB requested
- Future: search for long-lived particles (not necessarily SUSY)
  - Judith Höfer (postdoc)
  - Michaela Arampatzi, PhD student in National Technical U Athens (co-supervised by VAM)

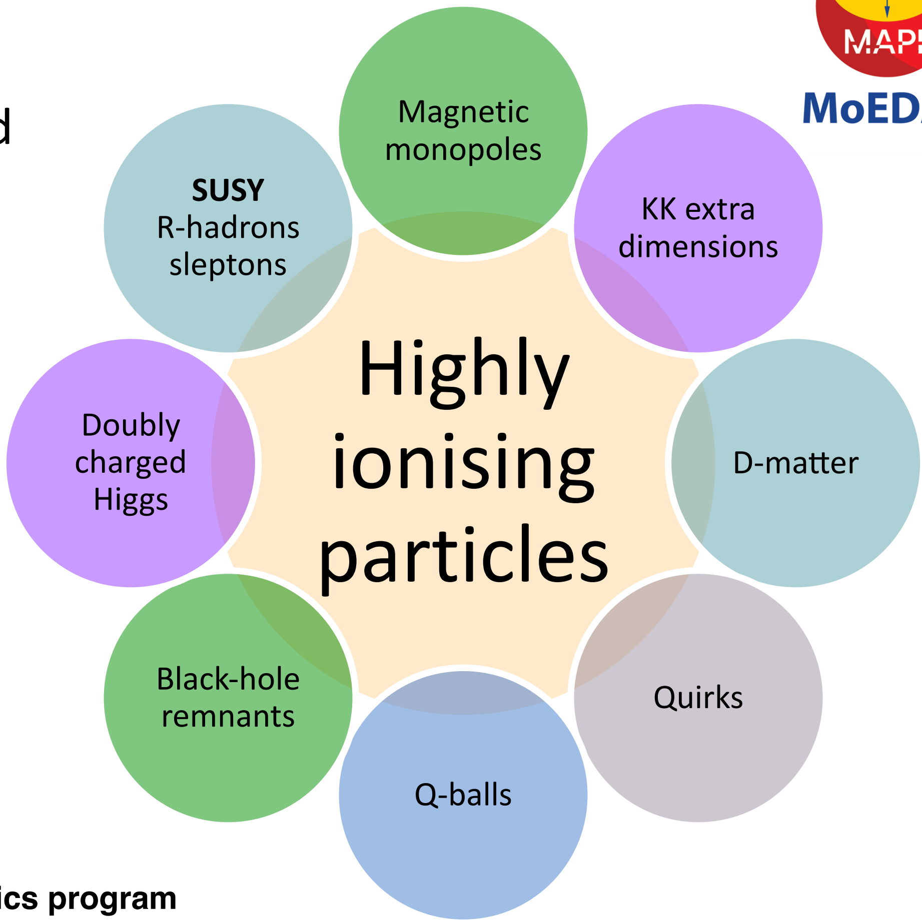


MoEDAL-MAPP experiment

MoEDAL physics goals

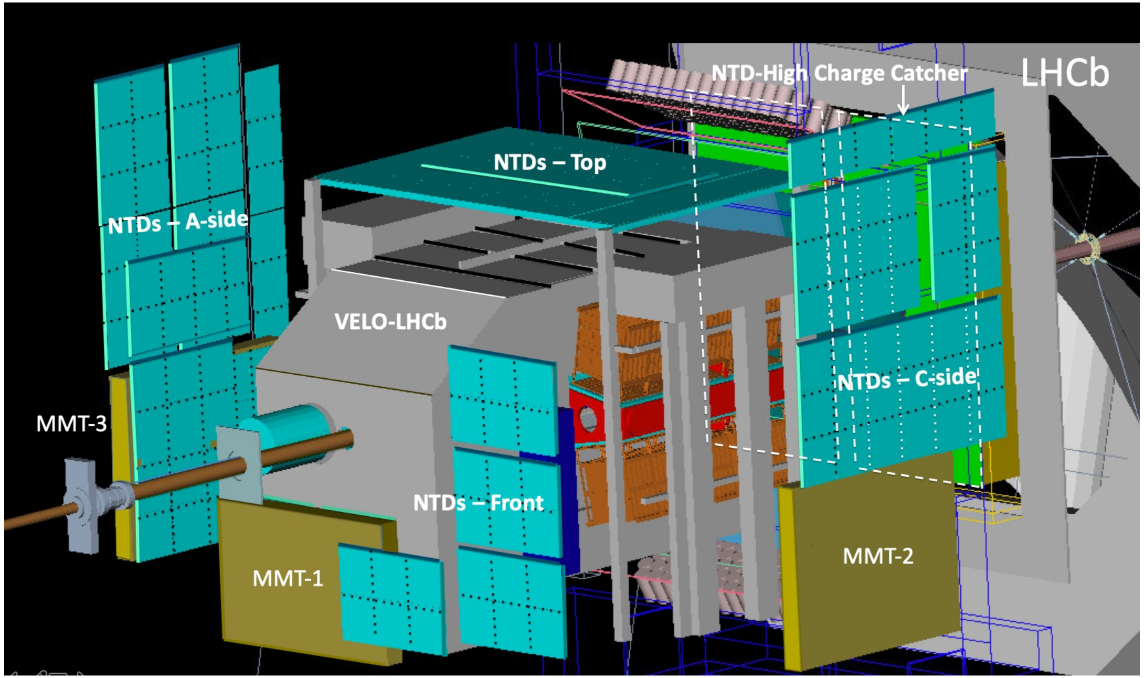
- MoEDAL baseline detector optimised for the detection of (meta)stable **highly ionising** particles
  - high charges (**high z**)
    - magnetic → **monopoles**!
    - electric → High Electric Charge Objects (**HECOs**)
  - slow moving (**low β**) ⇒ massive

- **MAPP upgrade designed for particles with low ionisation & neutral particles**



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

Baseline MoEDAL detector



MoEDAL

DETECTOR SYSTEMS

① Nuclear Track Detectors (**NTD**)

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

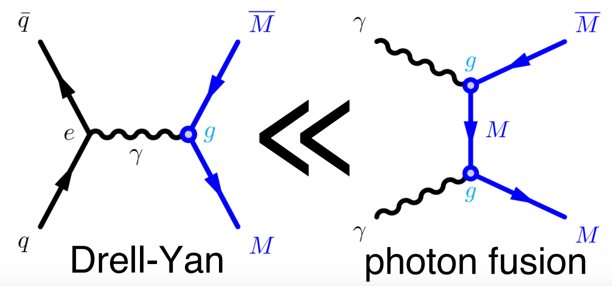
③ **TimePix** radiation background monitor

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

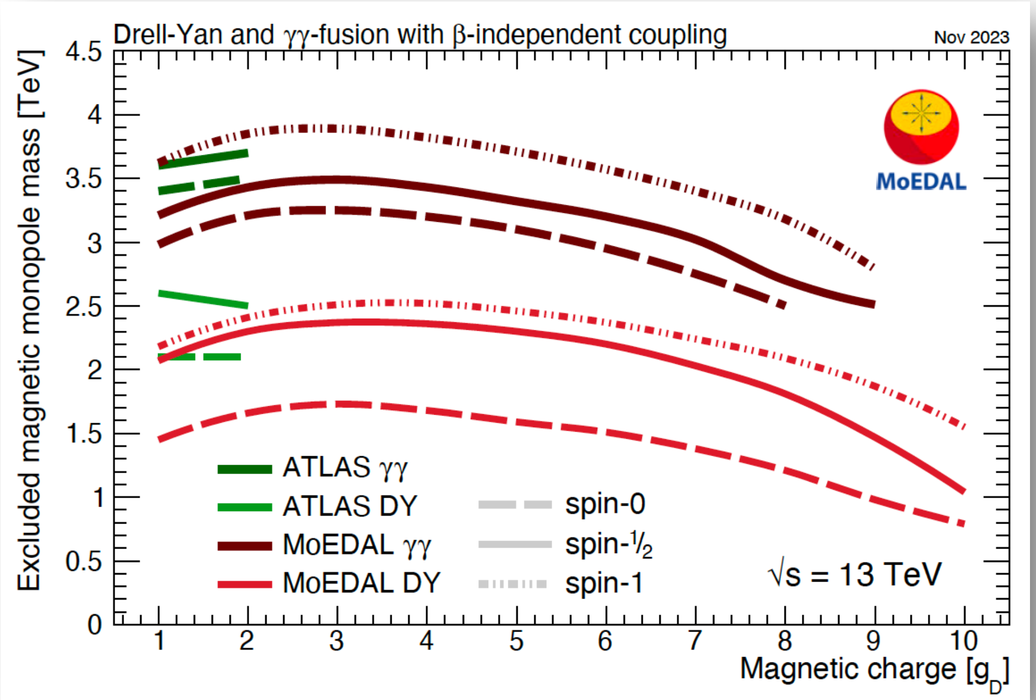
Magnetic monopole limits

- MoEDAL novelties in models
  - β-dependent coupling
  - spin-1 monopoles
  - γγ fusion
- MoEDAL set world-best collider limits for **|g| > 2 g_D**

$$\beta = \sqrt{1 - \frac{4M^2}{s}}$$

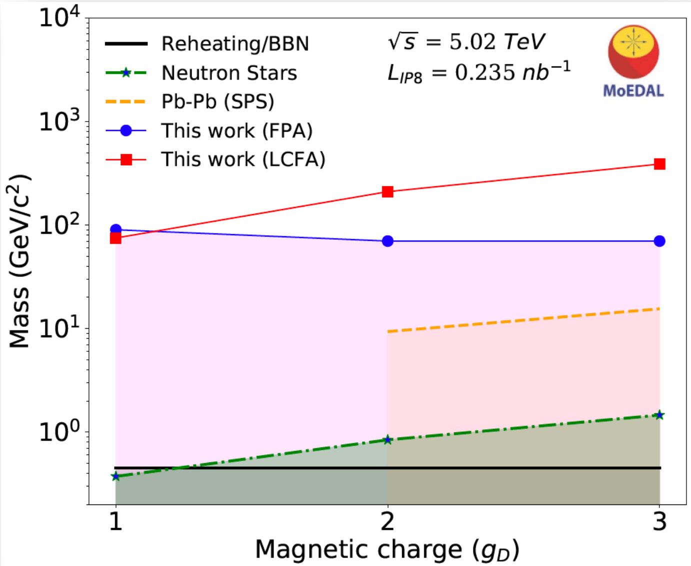


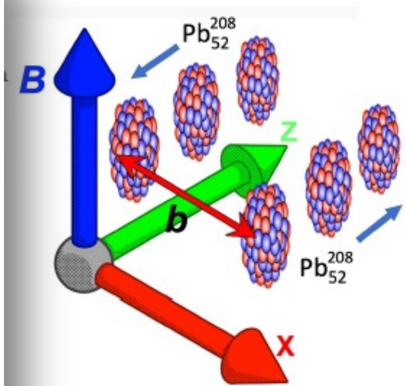
MoEDAL, [JHEP 08 (2016) 067](), [PRL 118 (2017) 061801](), [PLB 782 (2018) 510](), [PRL 123 (2019) 021802](), [PRL 126 (2021) 071801](), [Eur.Phys.J.C 82 (2022) 694](), [arXiv:2311.06509]()



See also:
- γ-fusion: Baines, Mavromatos, VAM, Pinfold, Santra, [Eur.Phys.J.C 78 (2018) 966]()
- monopole review: Mavromatos & VAM, [Int.J.Mod.Phys.A 35 (2020) 2030012]()

Monopoles via Schwinger mechanism





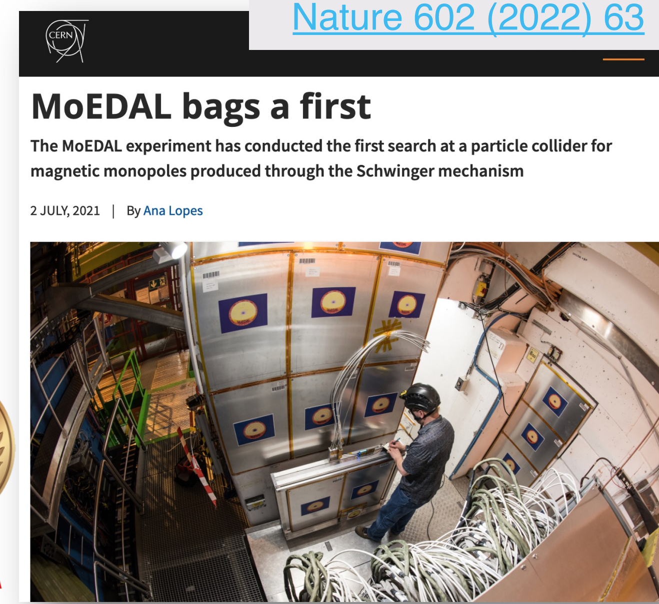
Monopole-antimonopole pairs may appear in strong magnetic fields present in heavy-ion collisions

- dual version of (original) mechanism to be studied in LUXE

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

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

Nature 602 (2022) 63



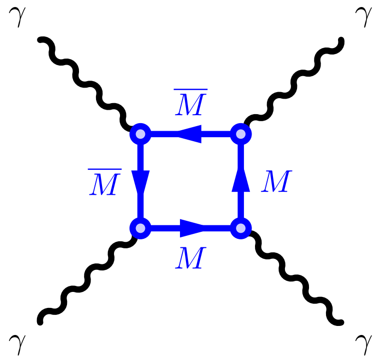
MoEDAL bags a first

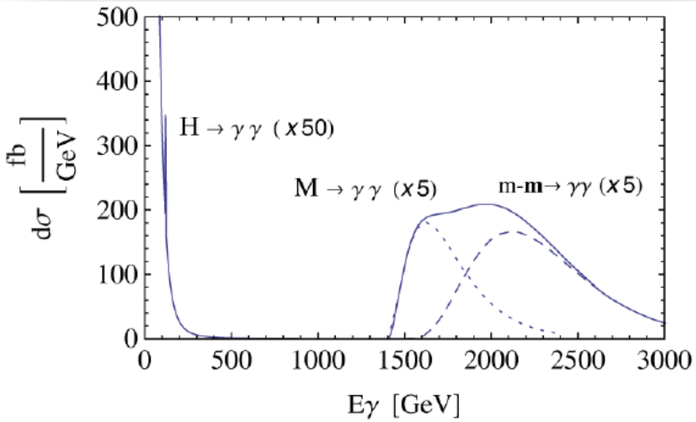
The MoEDAL experiment has conducted the first search at a particle collider for magnetic monopoles produced through the Schwinger mechanism

2 JULY, 2021 | By Ana Lopes

Indirect monopole searches in γγ events

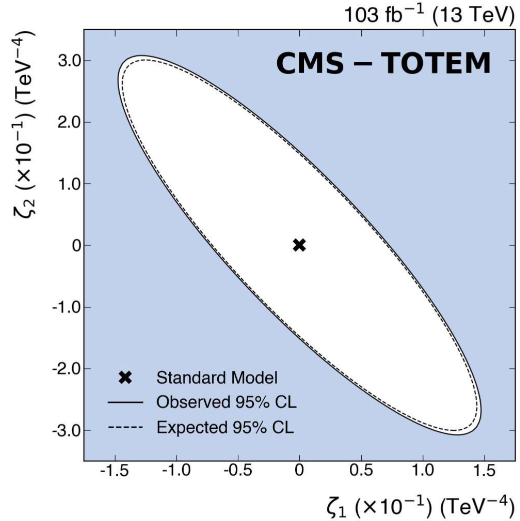
- Central exclusive γγ production (CEP)
  - light-by-light scattering in ultraperipheral collisions (UPC) of heavy-ions
  - in *pp* collisions with proton tagging: PPS (CMS-TOTEM) & AFP (ATLAS)
- Effective Field Theories & Born-Infeld interpretations lead to indirect limits on monopoles

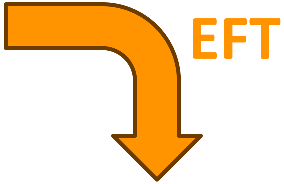




Epele, Fanchiotti, Garcia Canal, VAM, Vento, Eur.Phys.J.Plus 127 (2012) 60

CMS & TOTEM PPS, arXiv:2311.02725 [hep-ex]





$M_{MM} > |n|\ 4.18$ TeV

Good prospects for FCC and CLIC

Ellis, Mavromatos, Roloff, You, Eur.Phys.J.C 82 (2022) 634

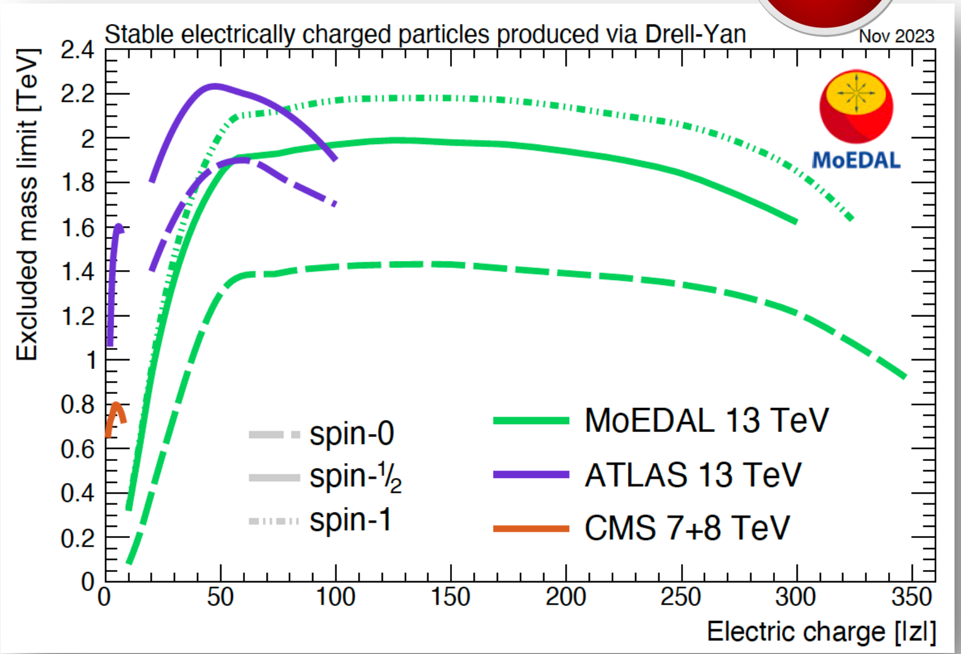
Musumeci & VAM, PoS(ICHEP2022)1025

Musumeci & VAM, *in progress*

High Electric Charge Objects (HECOs)

NEW

- Analysis based on NTDs
- Includes photon fusion
- Upper limits on production cross section as low as **1 fb**
- Limits on HECOs with electric charges in the range **5*e* – 350*e*** and masses up to ~**3300 GeV** (photon fusion)



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

arXiv:2311.06509 [hep-ex], subm. to PRL

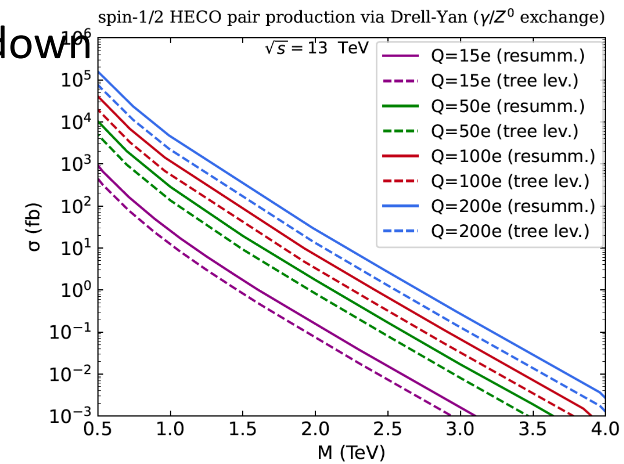
Good prospects for low electric charges: **1*e* – 8*e***

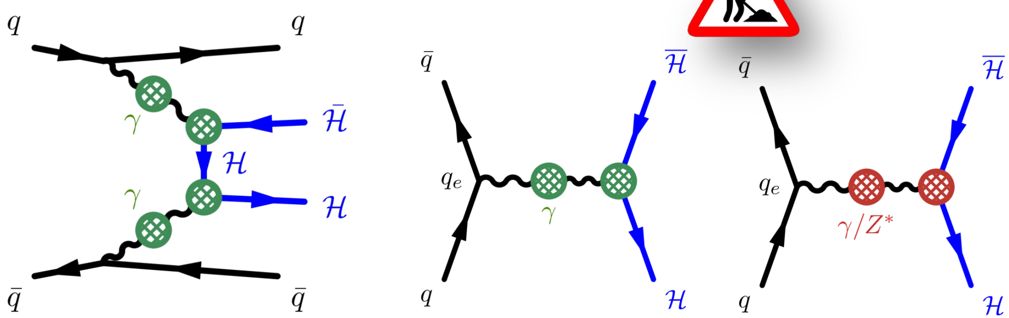
Altakach, Lamba, Masełek, VAM, Sakurai, EPJC 82 (2022) 848

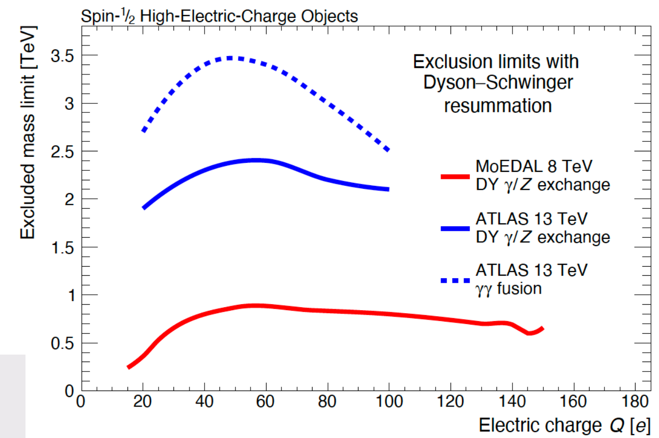
Previous results:
Eur.Phys.J.C 82 (2022) 694

Resummation for large coupling constants

- Large photon-HIP coupling ⇒ perturbation theory breaks down
- **Dyson-Schwinger** resummation for spin-½ HECOs
  - HECO effective mass much larger than bare mass
  - estimated cross section increases with resummation
  - experimental mass bounds more stringent
- Also, resummation for slow-moving monopoles
  - Alexandre, Mavromatos, PRD 100 (2019) 096005
  - ongoing preparation of UFO model



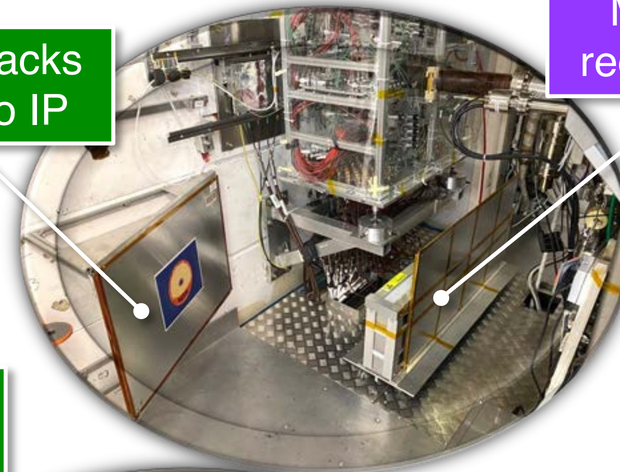




Alexandre, Mavromatos, VAM, Musumeci, Phys.Rev.D, to appear [arXiv:2310.17452]
Musumeci, PoS LHCP2023 (2024) 261

Upgraded MoEDAL installed for Run-3

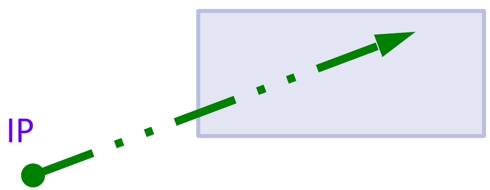
- Upgrades w.r.t. Run-2 MoEDAL
- Exposed to 2023 collisions
- Removed end of 2023 to allow for LHCb beampipe reworks
- To be re-installed in Feb 2024



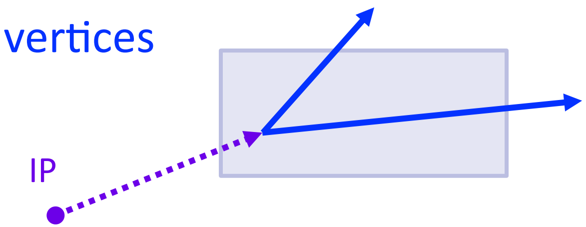
MAPP – MoEDAL Apparatus for Penetrating Particles

MoEDAL

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



MAPP-2: 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-1** installation in UA83 is underway
- **Phase-2 HL-LHC** (2029 –): Reinstall Phase-1 in UA83 and add **MAPP-2** in UGC1

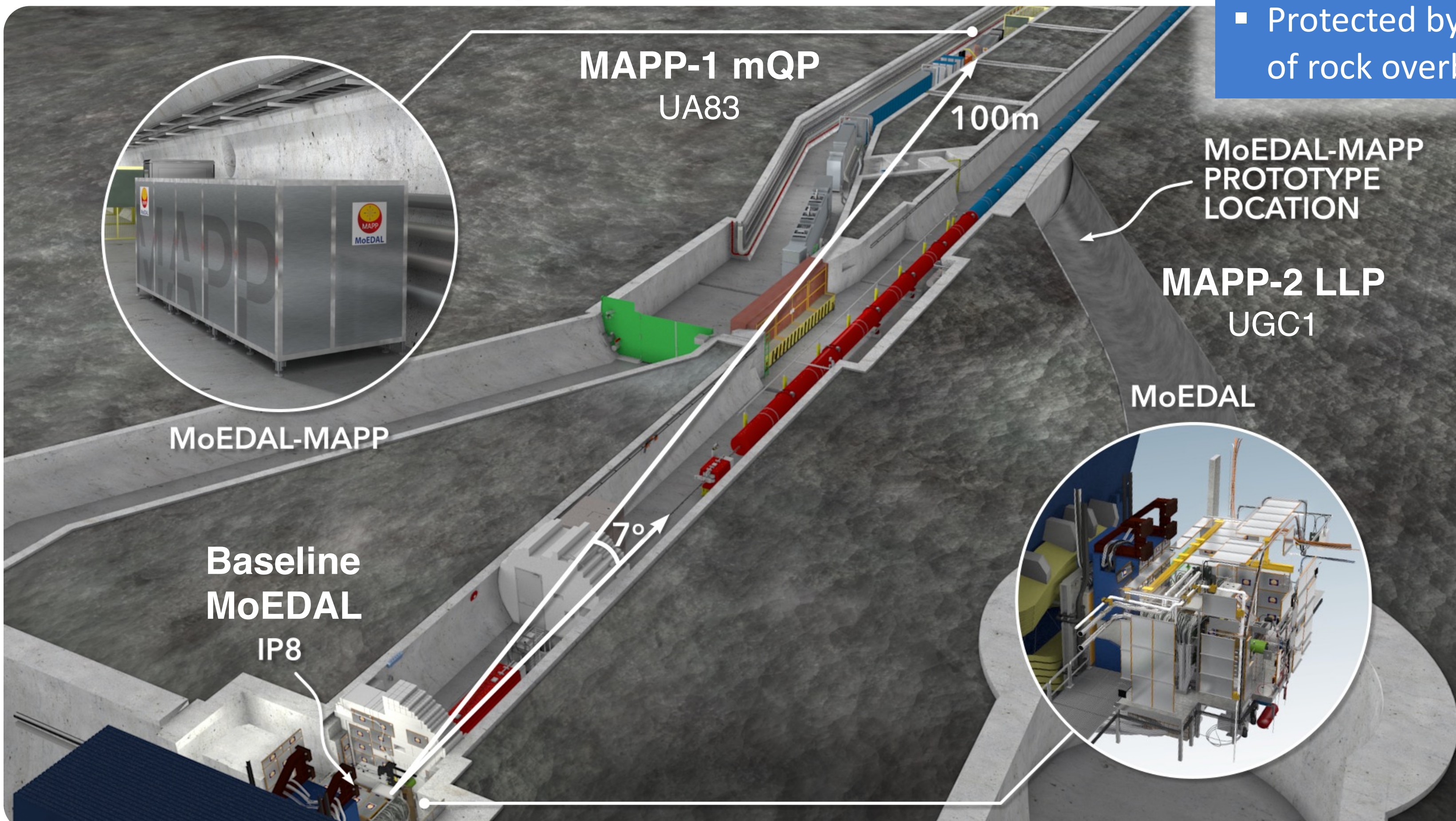
MoEDAL contribution to Snowmass, arXiv:2209.03988

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

☛ Details on MAPP physics in Michael's talk

MAPP location(s)

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



MAPP
MoEDAL

MAPP-1 installation

Emanuela to participate in Feb 2024 installation campaign

Work in progress and future plans

- *Beampipe searches for magnetic monopoles produced via the Schwinger effect by MoEDAL*
  - analysis of Run-1 CMS beampipe
  - sensitivity to extremely high charges
  - in MoEDAL-wide circulation – soon to appear on arXiv
- Resummation
  - scalar HECO theoretical work, UFO model & re-interpretation à la Dyson–Schwinger 

  - fermion monopole $U(1)_{strong}$ coupling for slow-moving monopoles ➞ UFO model 

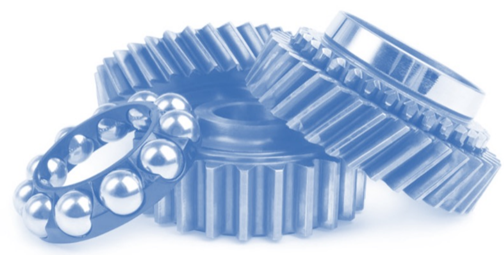
- Indirect searches for monopoles with diphotons
  - EFT & Born Infeld with CMS-TOTEM and ATLAS-AFP results 

  - monopolium constraints from ATLAS & CMS diphoton analyses
- MAPP
  - installation & commissioning 

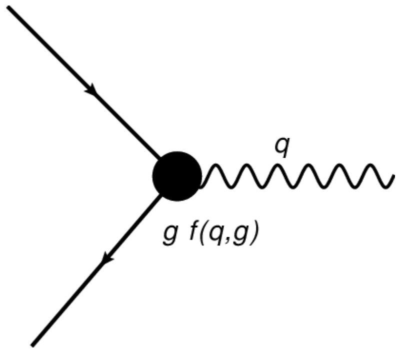
  - mCP prospects ➞ MAPP [Staelens, VAM et al, arXiv:2311.02185] and other? 

  - analysis with 2024 data
- MoEDAL Run-3 data analysis

Spares



Monopole properties in a nutshell

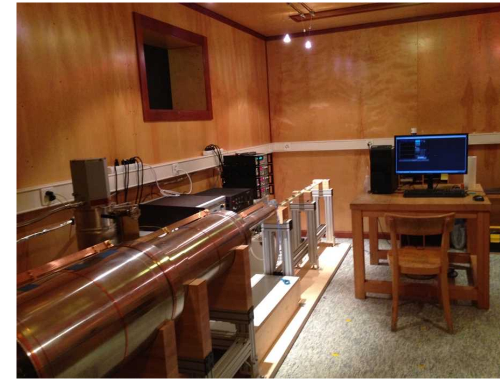


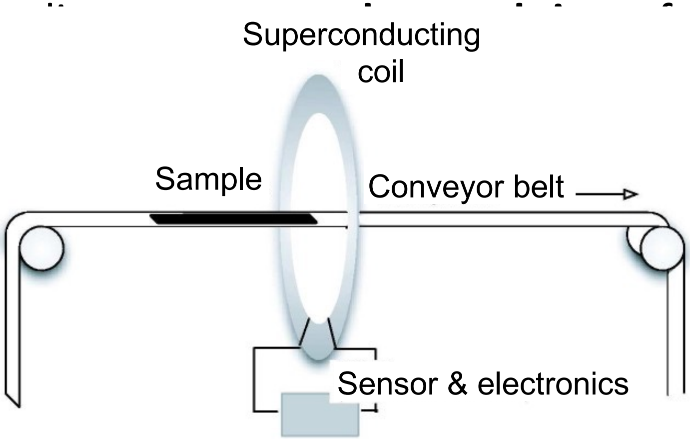
- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges integer multiples of g_D: $g = ng_D$, $n = 1, 2, ...$
- Photon-monopole coupling constant
  - large: $g/\hbar c \sim 20$ (precise value depends on units)
  - following duality arguments, may be β-dependent, $\beta = \sqrt{1 - \frac{4M^2}{s}}$
- Dirac monopole is a point-like particle; GUT monopoles are extended objects
- Monopole spin and mass not determined by theory → free parameters
- Monopole interaction with matter: high ionisation, Cherenkov radiation, multiple scattering

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

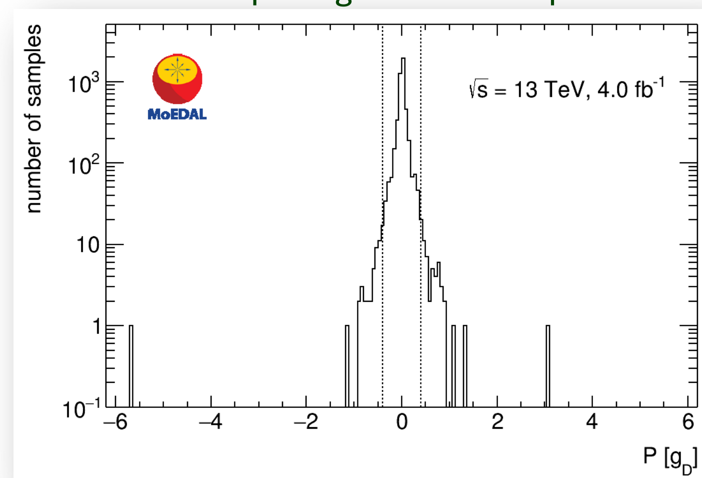
MMT scanning

- MMTs scanned through the SQUID at *ETH Zurich*
- MMT bars are cut into pieces and fed into the SQUID **two or more times**, depending on scanning campaign
- Instabilities can be caused by several *known* instrumental and environmental factors
- rther





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

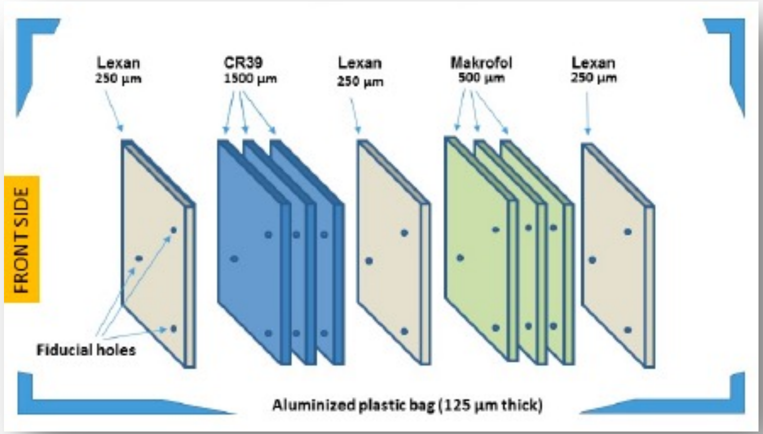


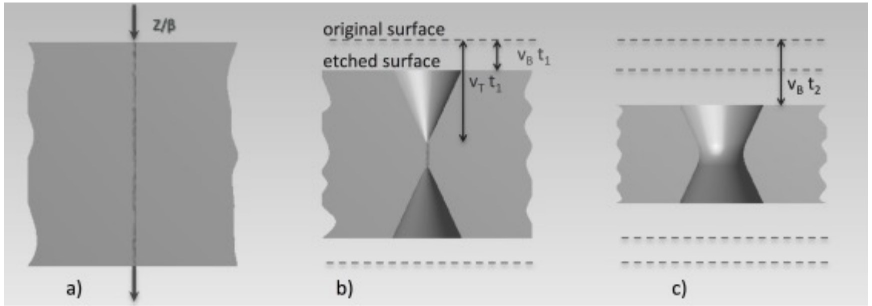
MoEDAL, PRL 123 (2019) 021802

No isolated magnetic charges found in MMT analyses

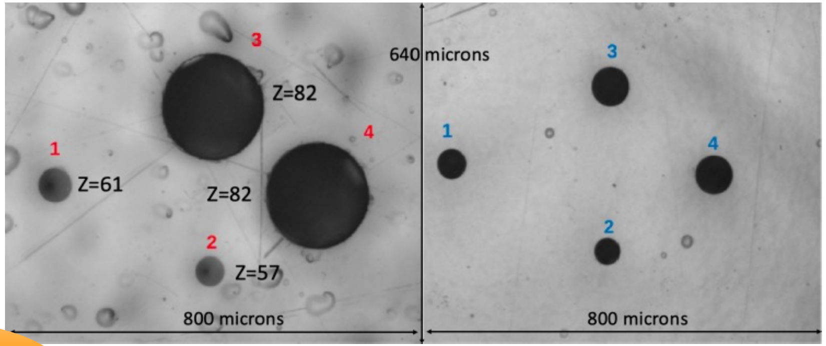
NTD+MMT search for HECOs (and monopoles)

- **First NTD analysis for MoEDAL**
- Prototype NTD array of 125 stacks (7.8 m^2) exposed to 8 TeV *pp* collisions (Run 1)
- NTDs etched and scanned in INFN Bologna





Strong etching
Soft etching



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

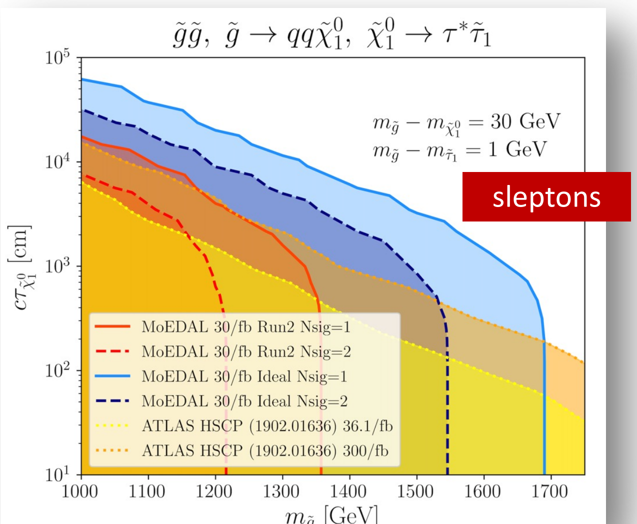
No HIP candidates found in the NTDs stacks

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

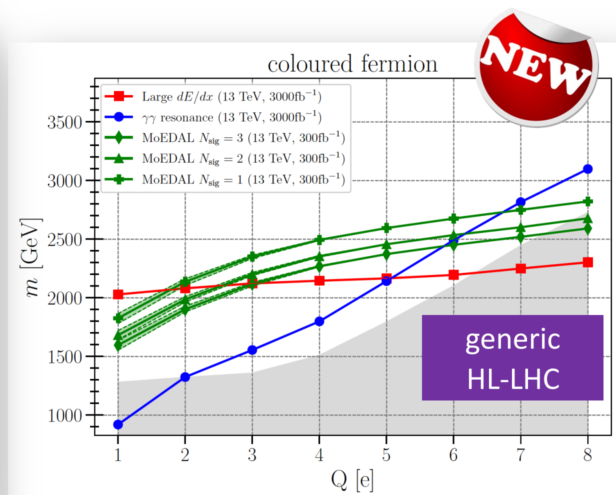
"Low" electric charges

- Supersymmetric singly charged LLPs: sleptons, R-hadrons, charginos [Felea, VAM et al, EPJC 80 (2020) 431]
- **Generic multiply charged particles** [Altakach, Lamba, Masełek, VAM, Sakurai, EPJC 82 (2022) 848]
- Also, models of ν masses → 2-, 3-, 4-ply charged [Hirsch et al, EPJC 81 (2021) 697]

→ possible explanation of excess in dE/dx events in ATLAS pixel [arXiv:2205.06013]



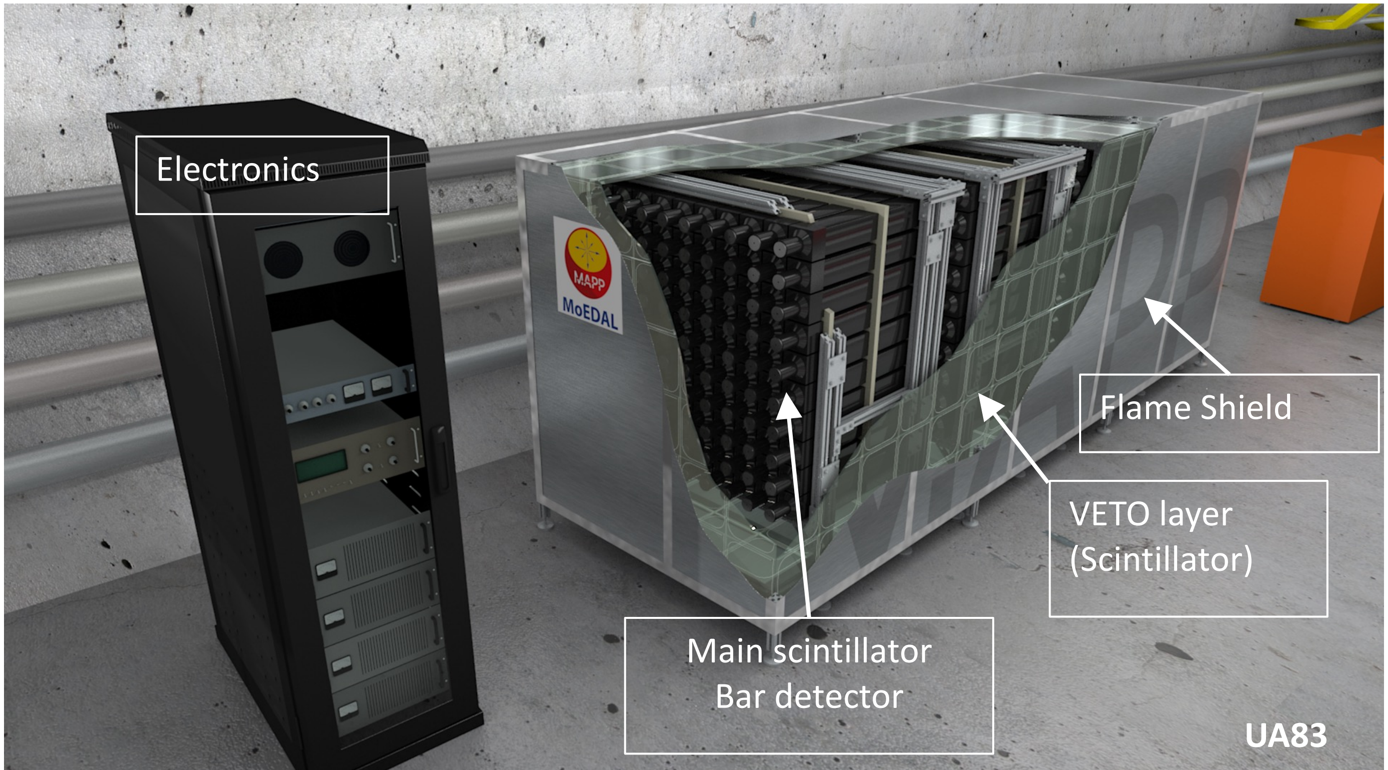
Felea, VAM et al, EPJC 80 (2020) 431



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

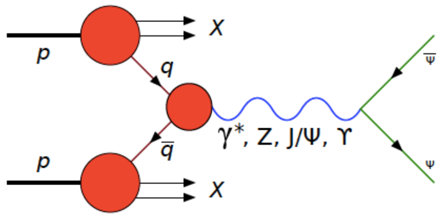
MoEDAL has the best sensitivity at intermediate electric charges at HL-LHC

MAPP-mQP Phase-1 detector concept

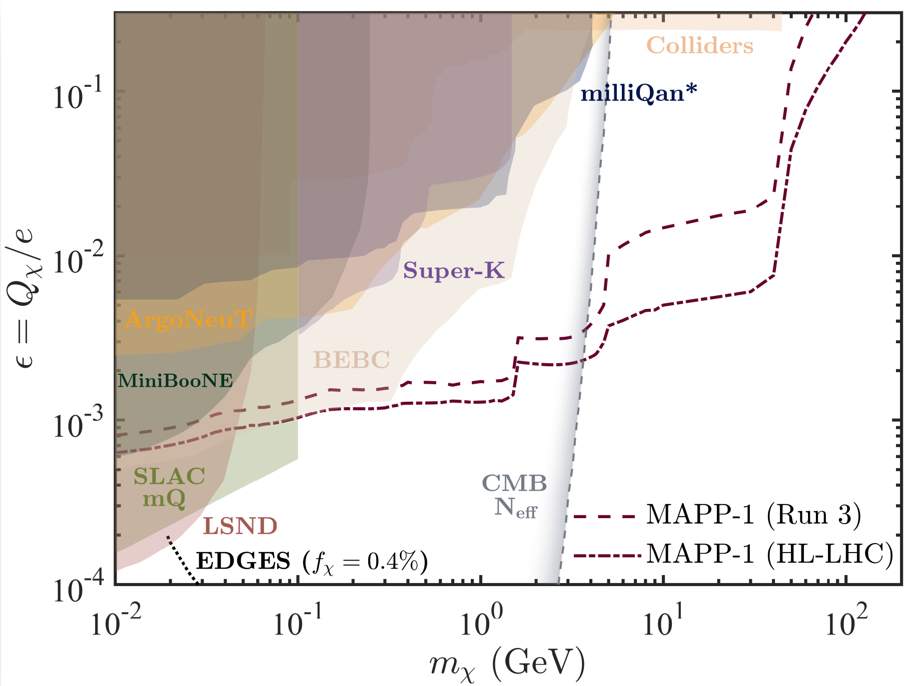


- 400 scintillator bars ($10 \times 10 \times 75\ cm^3$) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

Millicharged particles



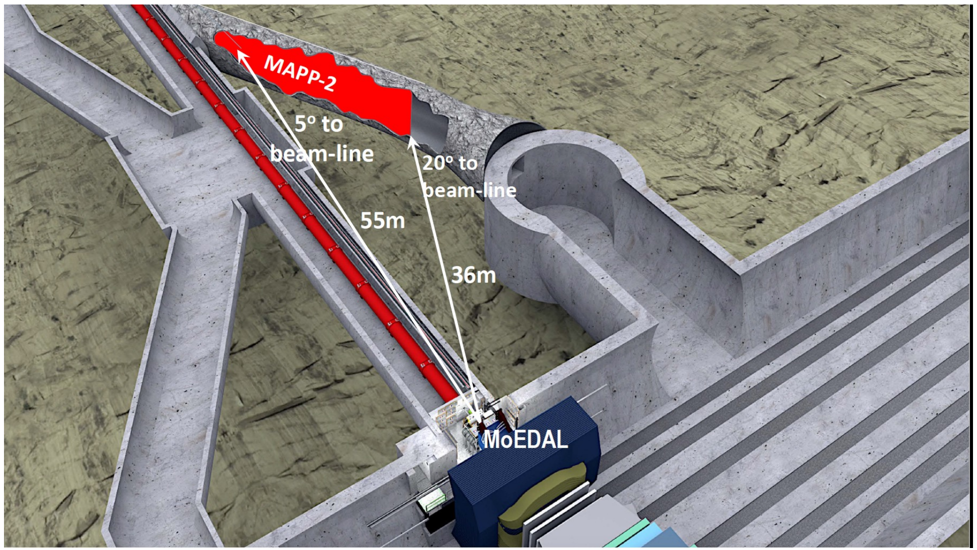
- mCP generated by **massless dark photon**, kinetically mixed with SM, that couples to millicharged χ
- Production through Drell-Yan and meson decays
- Millicharged strongly interacting DM (**mSIDM**)
  - mCPs can account for a fraction of DM abundance
  - can escape from underground direct-detection detectors
  - mCP results are recasted to mSIDM

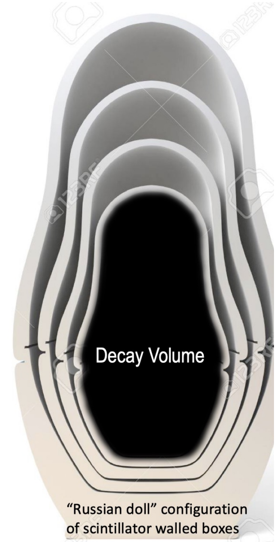


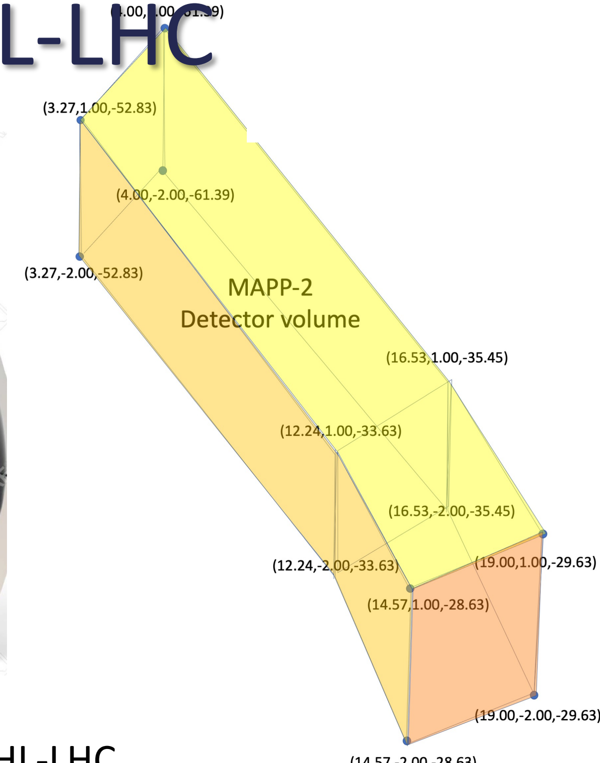
VAM, de Montigny, Mukhopadhyay, Ouimet, Pinfold, Shaa, Staelens, arXiv:2311.02185

MAPP also sensitive to **heavy neutrino** with large **electric dipole moment**, experimentally similar to mCP [Frank et al, Phys.Lett.B 802 (2020) 135204

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



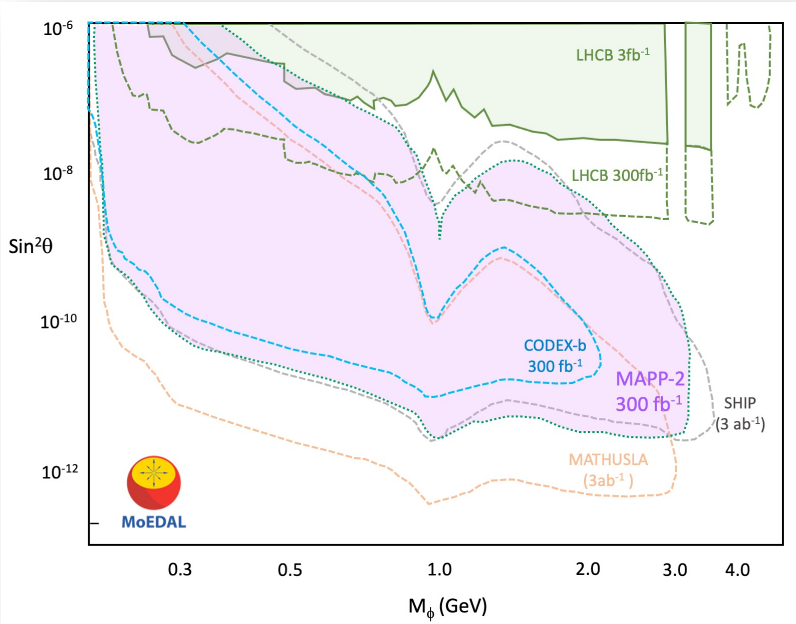




- The UGC1 gallery will be prepared during Long Shutdown 3 prior to HL-LHC
- MAPP-2 detector extends to the full length of the UGC1 gallery
- Detector technology: large scintillator tiles with optical fibre readout
- Tracking detectors formed by 3 or 4 hermetic containers – one within the other – lining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

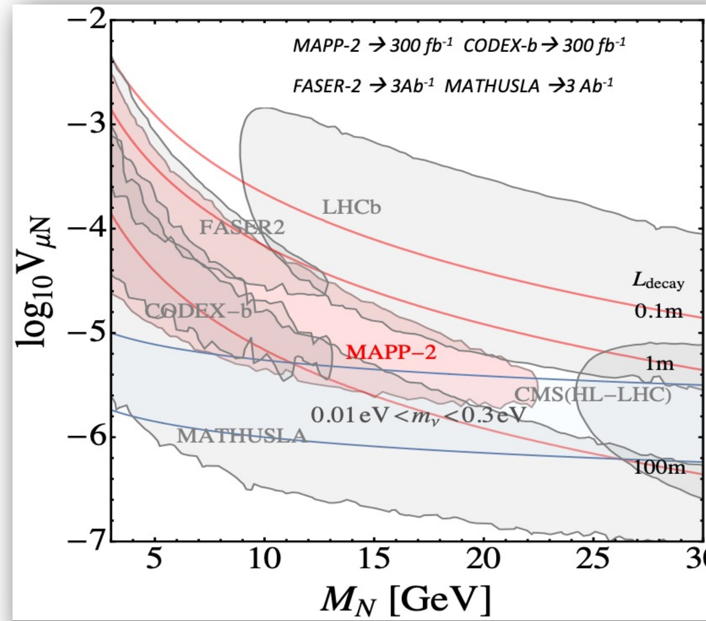
MAPP-LLP – dark matter & heavy neutrinos

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