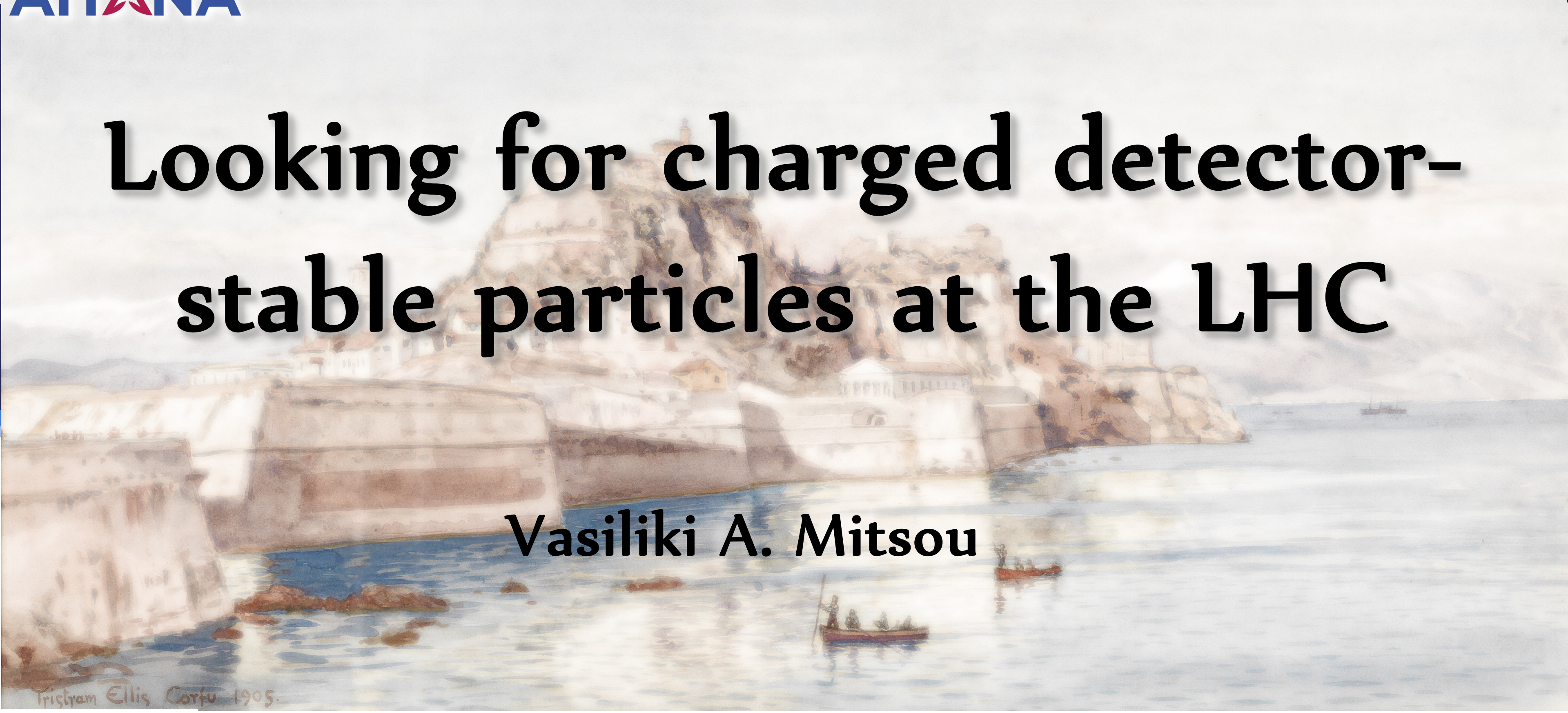
AITANA

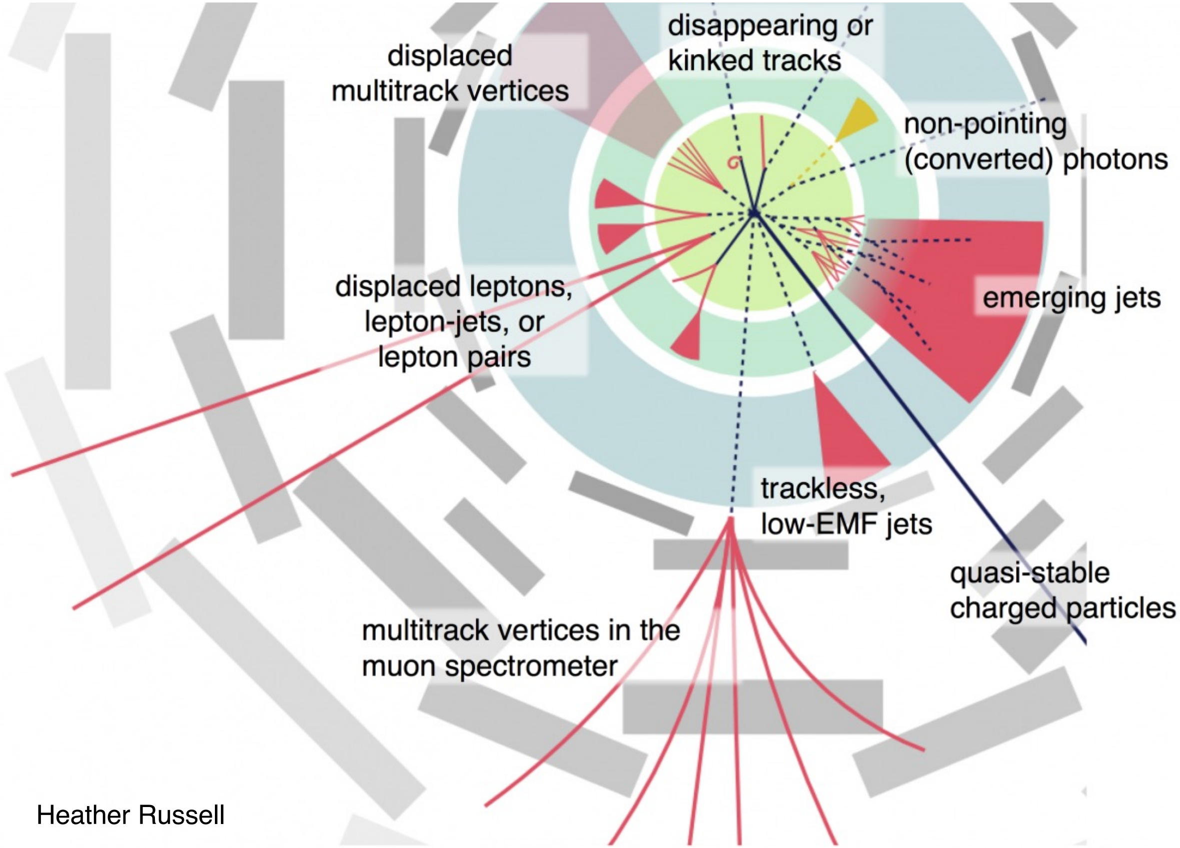
Looking for charged detector-stable particles at the LHC



Vasiliki A. Mitsou

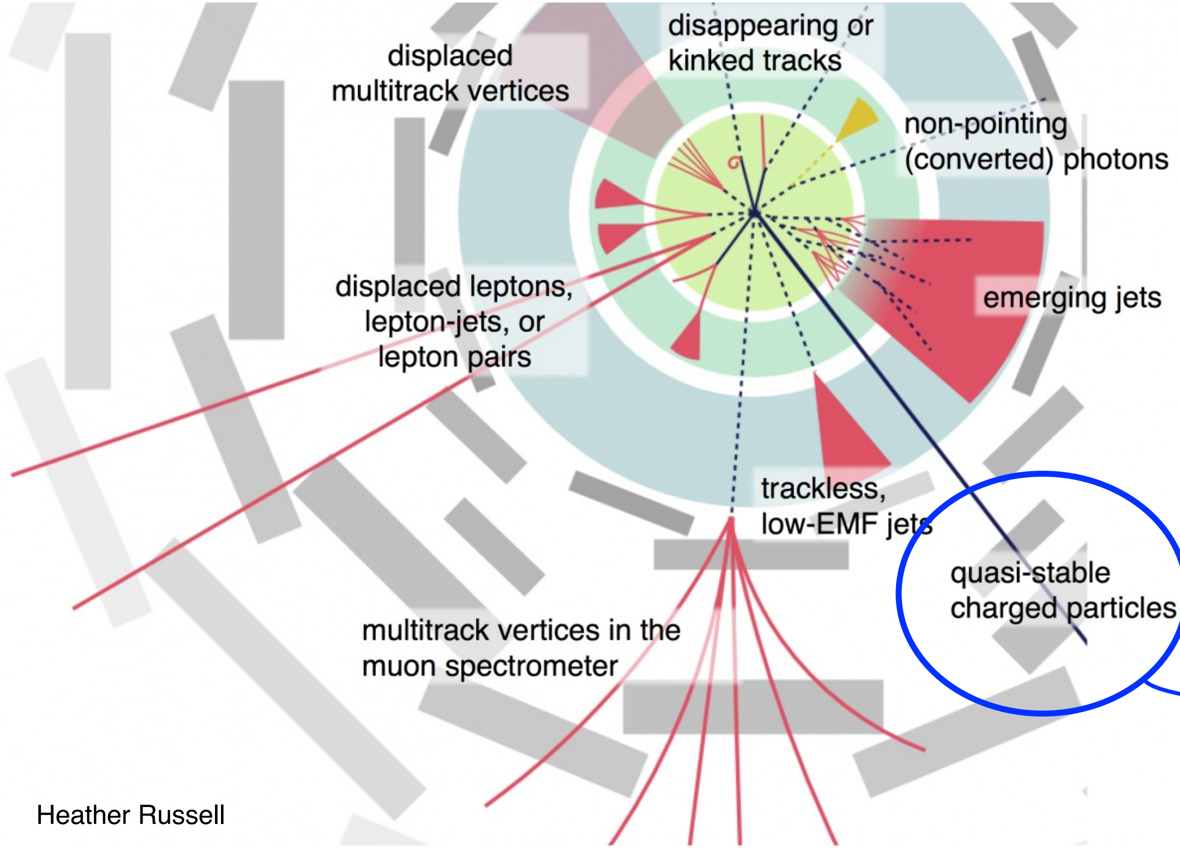
23rd HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY
Workshop on the Standard Model and Beyond
August 27 – September 7, 2023, Corfu, Greece

Lifetime frontier



- Physics beyond the Standard Model has not appeared in searches so far
- Maybe we are not looking at the right signals
- Long-lived particles may be the answer

Lifetime frontier



- Physics beyond the Standard Model has not appeared in searches so far
- Maybe we are not looking at the right signals
- Long-lived particles may be the answer!

focus of this talk

High ionisation

Highly ionising particles (**HIPs**) characterised by one *or both* of these properties:

→ high charges (**high z**) ⇒ **electric** and/or **magnetic** charges

→ slow moving (**low β**) ⇒ **massive** particles

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

Electric charge – Bethe-Bloch formula

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

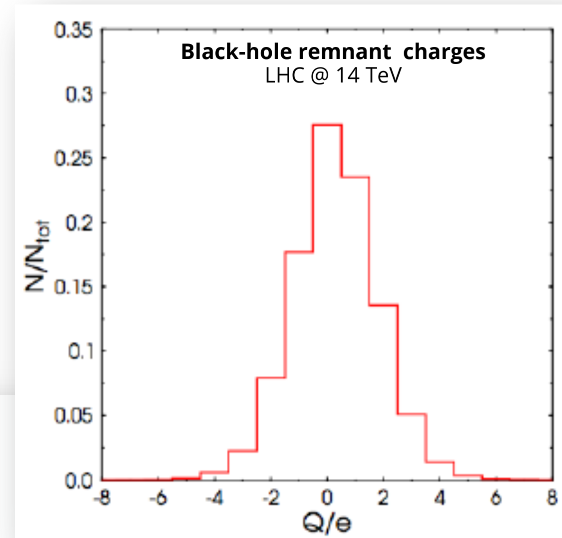
$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I_m}+\frac{K|g|}{2}-\frac{1}{2}-B(g)\right]$$

Magnetic charge

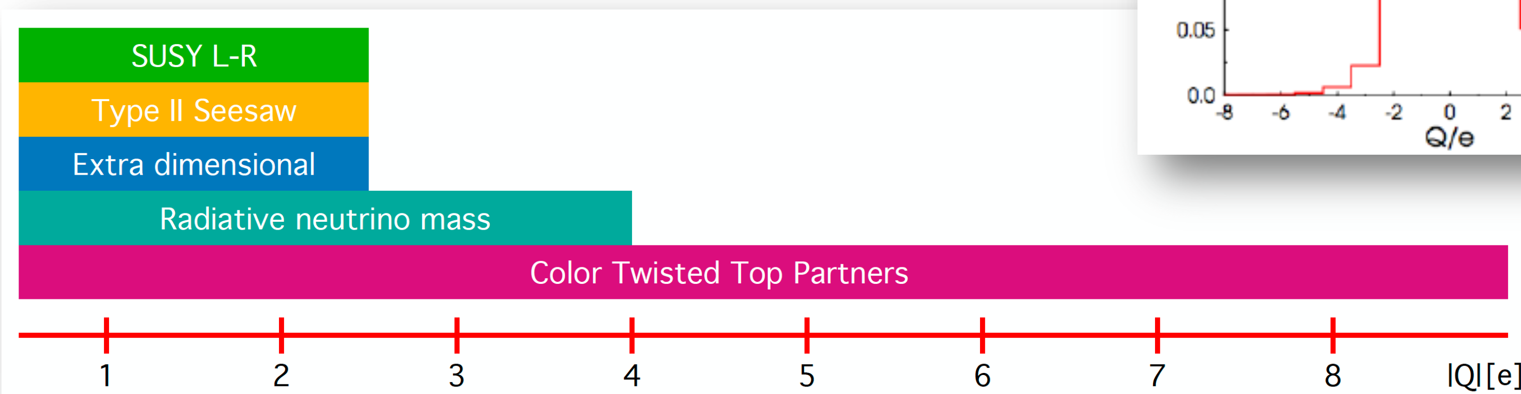
Bethe-Ahlen formula

Multiply charged quasi-stable particles

- High Electric Charge 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

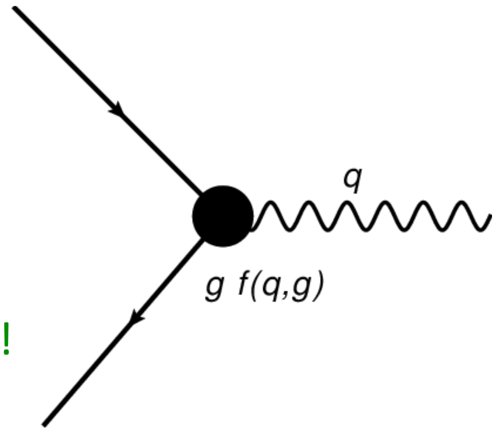


Hossenfelder, Koch, Bleicher, hep-ph/0507140



R. Masełek, DISCRETE2020-2021

Magnetic monopoles in a nutshell

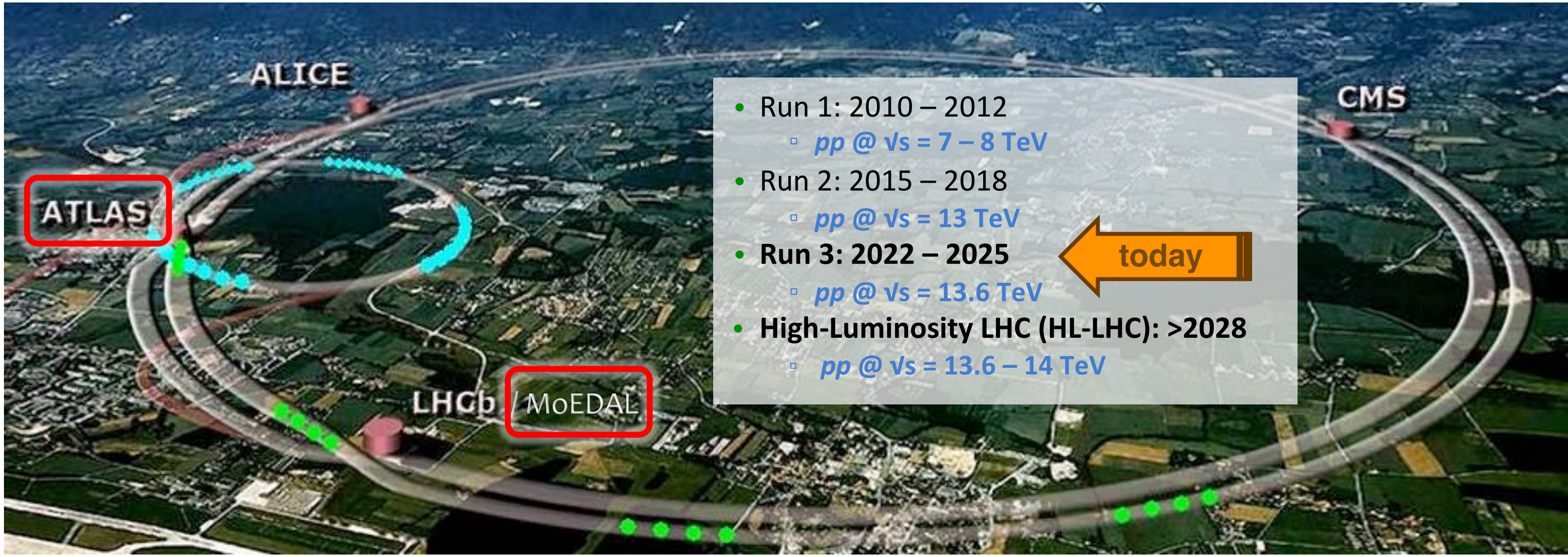


- Why? Because they symmetrise Maxwell's equations
  - electric ↔ magnetic charge duality
- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges are integer multiples of Dirac charge: $g = ng_D$, $n = 1, 2, \ldots$
  - > 4700 times more ionising than a minimum ionising particle!
- 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 is not determined by theory → free parameter
- Monopole mass not theoretically fixed → free parameter

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

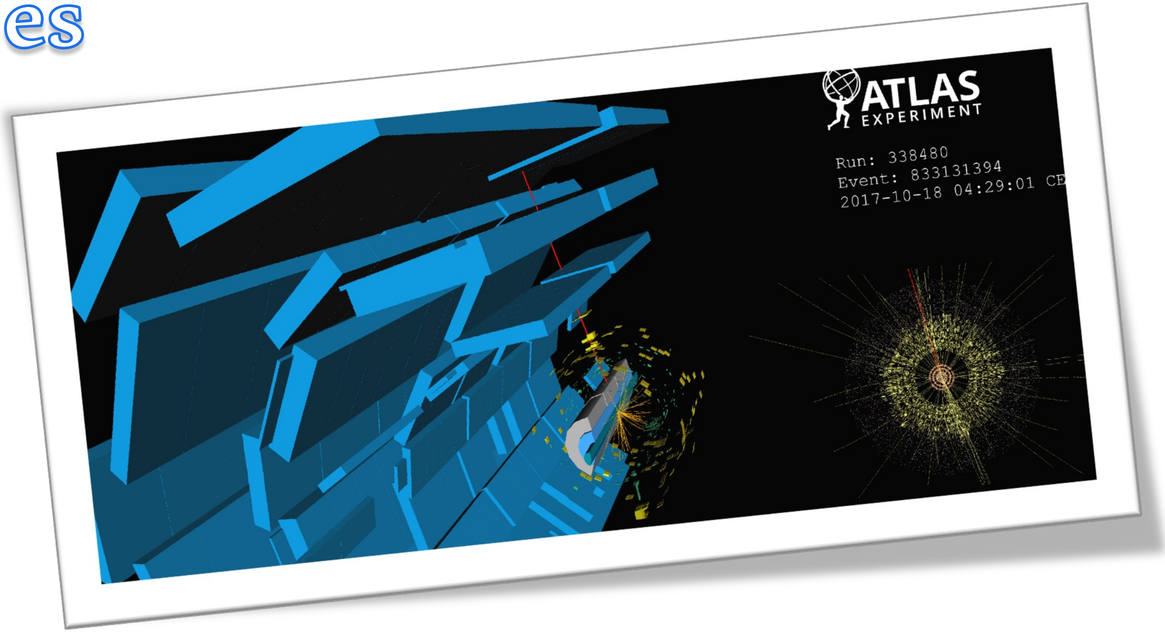
Large Hadron Collider at CERN

- ATLAS and MoEDAL perform searches for magnetic monopoles & HECOS
- MoEDAL receives ~10–50 times less luminosity than ATLAS
- Complementarity
  - ATLAS general-purpose; based on electronic readout
  - MoEDAL dedicated to (meta)stable particles; mostly passive detectors



ATLAS searches

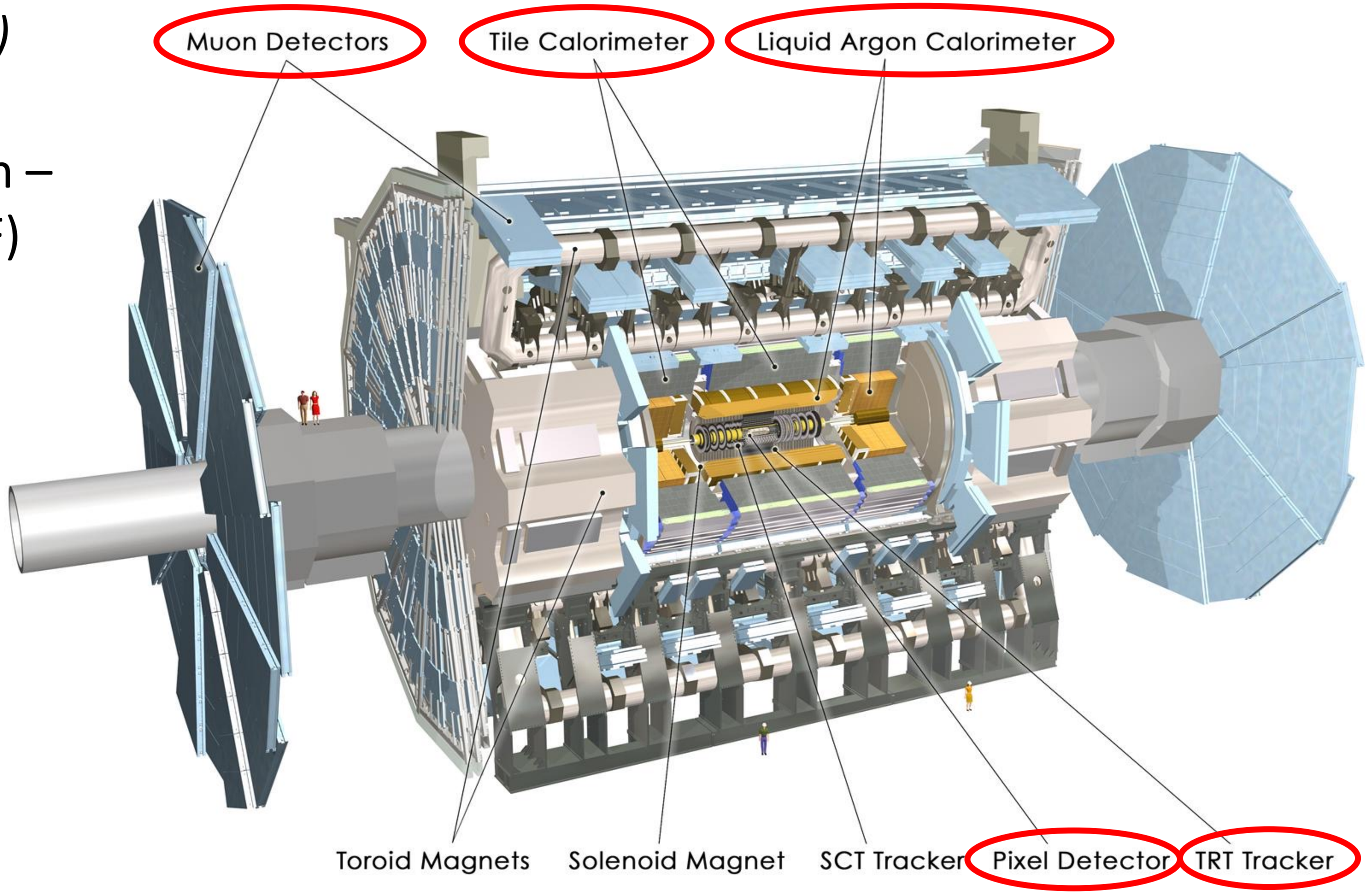
- dE/dx in pixel detector
- Large dE/dx + ToF
- Multiply charged particles
- Monopoles and HECOs



See also Xuai Zhuang's and Jun Guo's talks

ATLAS sub-systems for HIP searches

1. Energy loss *(dE/dx)* measurements
2. Timing information – Time-of-Flight (ToF)

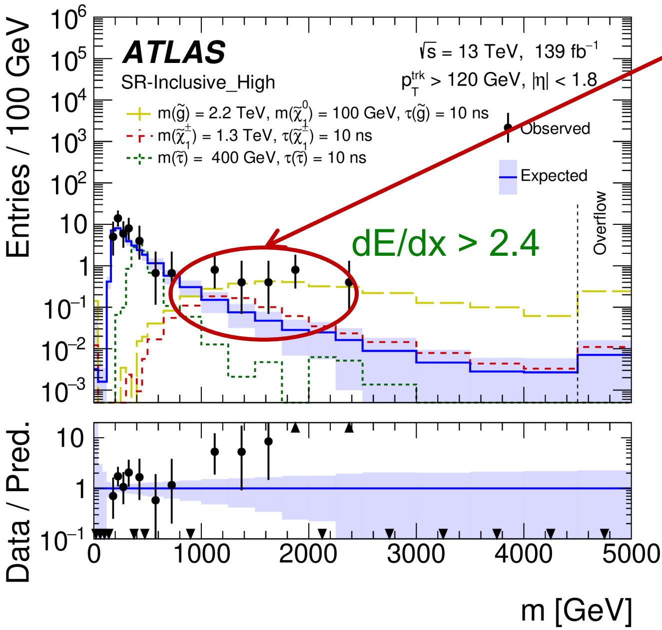


2022: *dE/dx* in pixel detector

JHEP 06 (2023) 158

- Wide sensitivity to charged, long-lived, massive particles with lifetimes of ~ns to stable ➜ gluinos, charginos, sleptons
- Pixel detector provides ionisation measurements ($\sigma \approx 12\%$) along each track

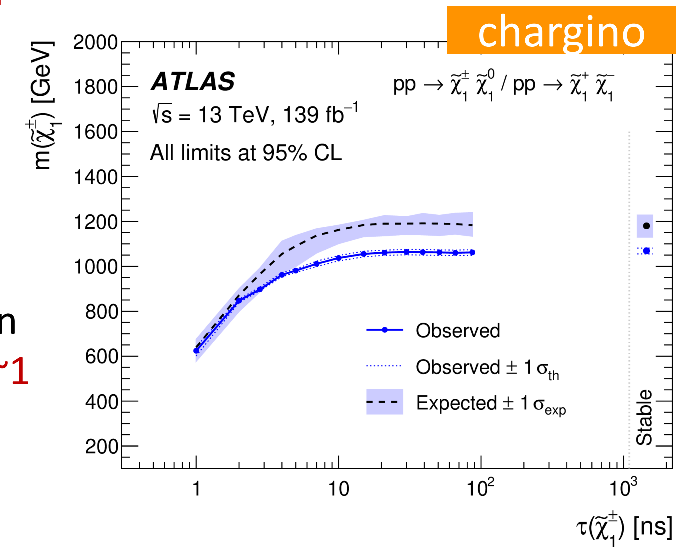
Excess 2.4σ in mass bin of 600 GeV gluino seen in 36.1 fb^{-1} search [Phys. Lett. B 788 (2019) 96] not confirmed



7 observed, 0.7±0.4 expected
3.3σ global excess

$$m_{\mathrm{d}E/\mathrm{d}x} \equiv \frac{p_{\mathrm{reco}}}{\beta\gamma(\langle \mathrm{d}E/\mathrm{d}x\rangle_{\mathrm{corr}})}$$

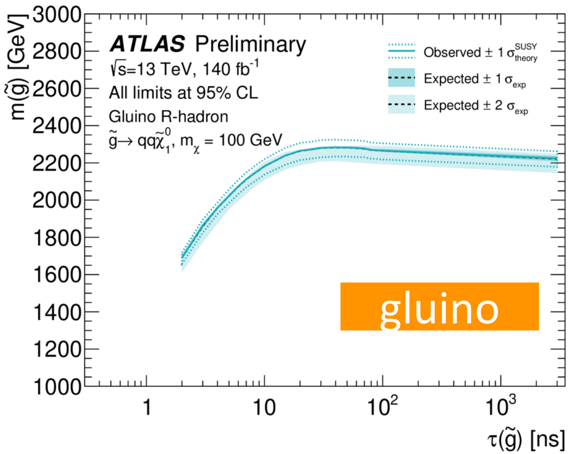
These 7 charged particles seen in calorimeter & muon systems, which estimate *β*~1 ➜ inconsistent with signal model, if *z* = 1

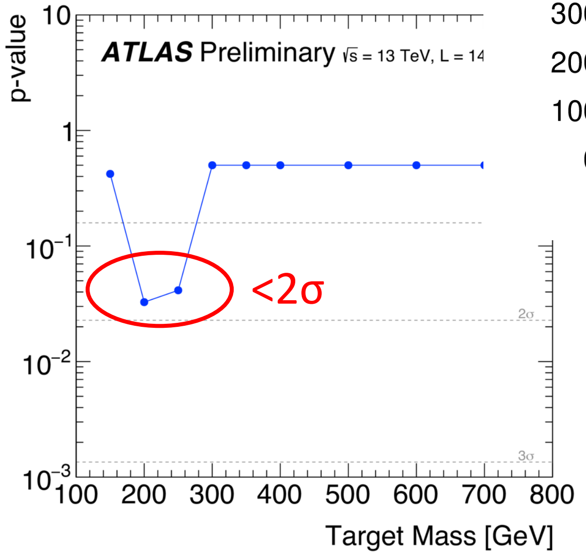


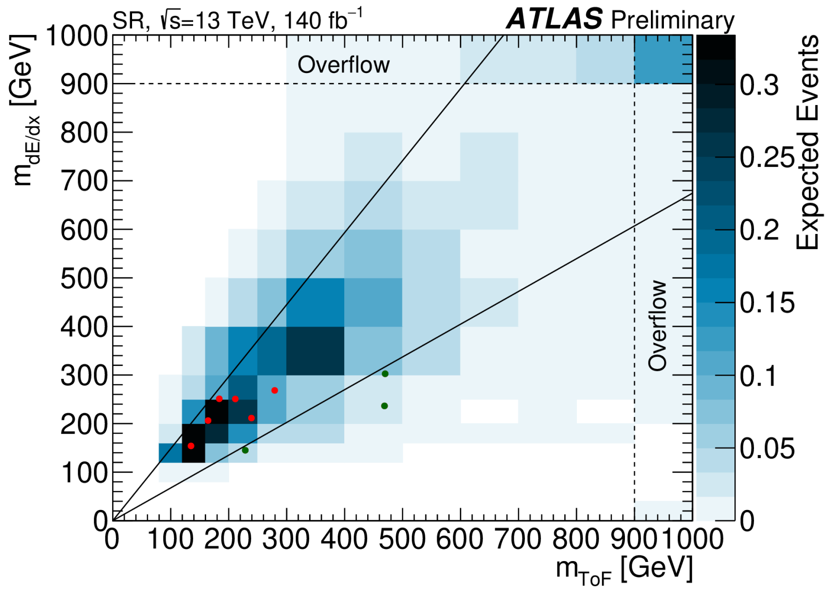
Large dE/dx + ToF

ATLAS-CONF-2023-044

- Targeting singly charged massive charged slow particles: m > 100 GeV, τ > 3 ns
- Based on measurement of anomalously large ionisation energy loss in ID tracker
- Improves 2022 search [JHEP 06 (2023) 158] by ToF measured by hadronic calorimeter





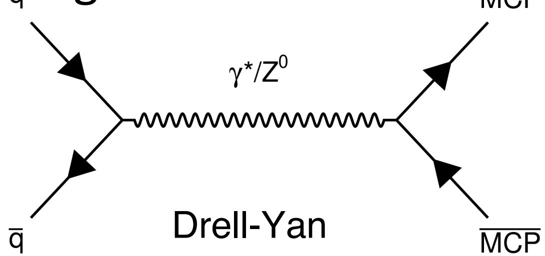


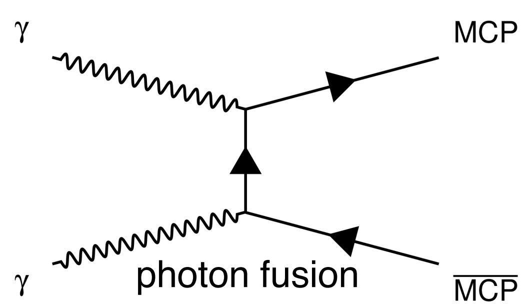
Agreement with background expectation
- observed 6 events in signal region
- expected 5.1±0.5 background events

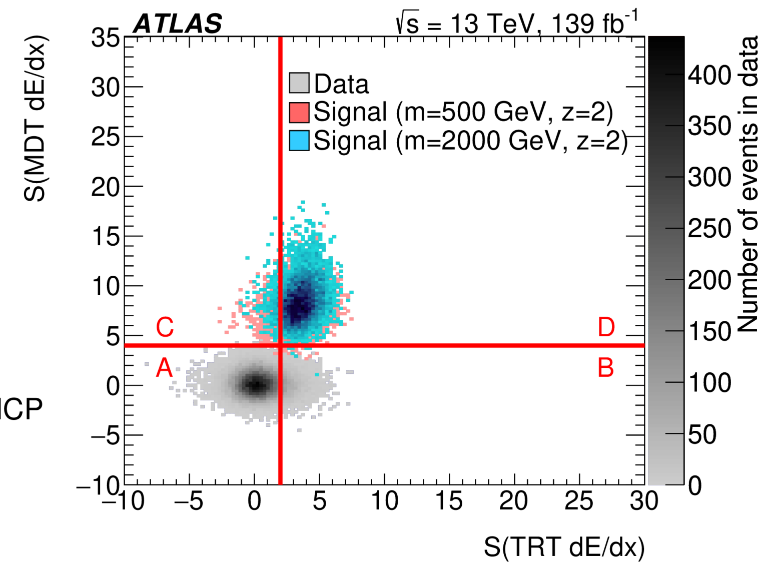
Multiply charged particles

arXiv:2303.13613

- Searching heavy particles of charge $2e \leq z \leq 7e$
- Detectors
  - Pixel, TRT, muon MDT → dE/dx
  - high-threshold TRT hits
- Pixel used only in $z = 2$; saturated readout for higher z







$$S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}.$$

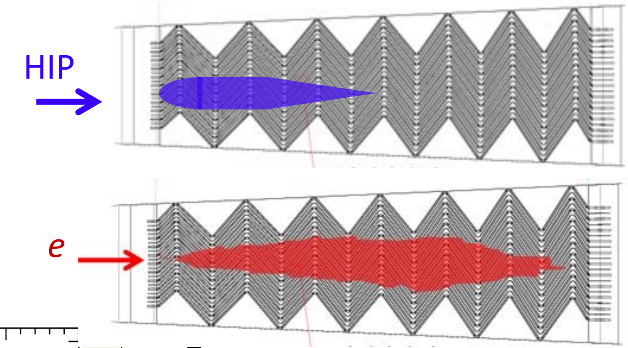
Search category	$N^{\mathrm{A\ observed}}_{\mathrm{data}}$	$N^{\mathrm{B\ observed}}_{\mathrm{data}}$	$N^{\mathrm{C\ observed}}_{\mathrm{data}}$	$N^{\mathrm{D\ expected}}_{\mathrm{data}}$	$N^{\mathrm{D\ observed}}_{\mathrm{data}}$
$z = 2$	41 674	5024	13	1.6 ± 0.4 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0

1.5σ excess

Monopoles and HECOs

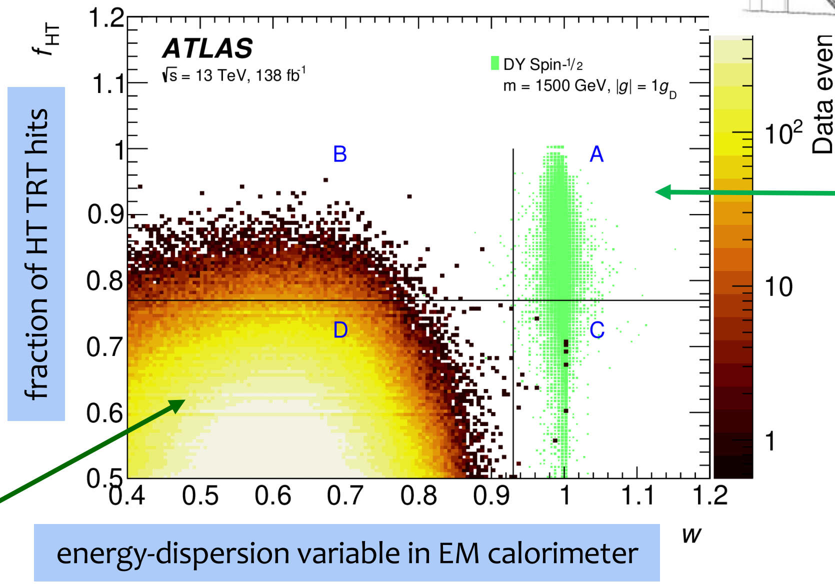
arXiv:2308.04835

- Two different signals:
  - **TRT**: large high-threshold (HT) hit fraction, f_{HT}, due to HIP & associated δ-electrons
  - **EM calorimeter**: HIPs slow down (and usually stop) there, leaving a pencil-shape energy deposit, unlike extensive showers from (much lighter) electron
- No events observed in signal region A



0.15 ± 0.04 (stat) ± 0.05 (syst) background events expected, estimated as

$N_A^{exp} = N_B N_C / N_D$ (ABCD method)



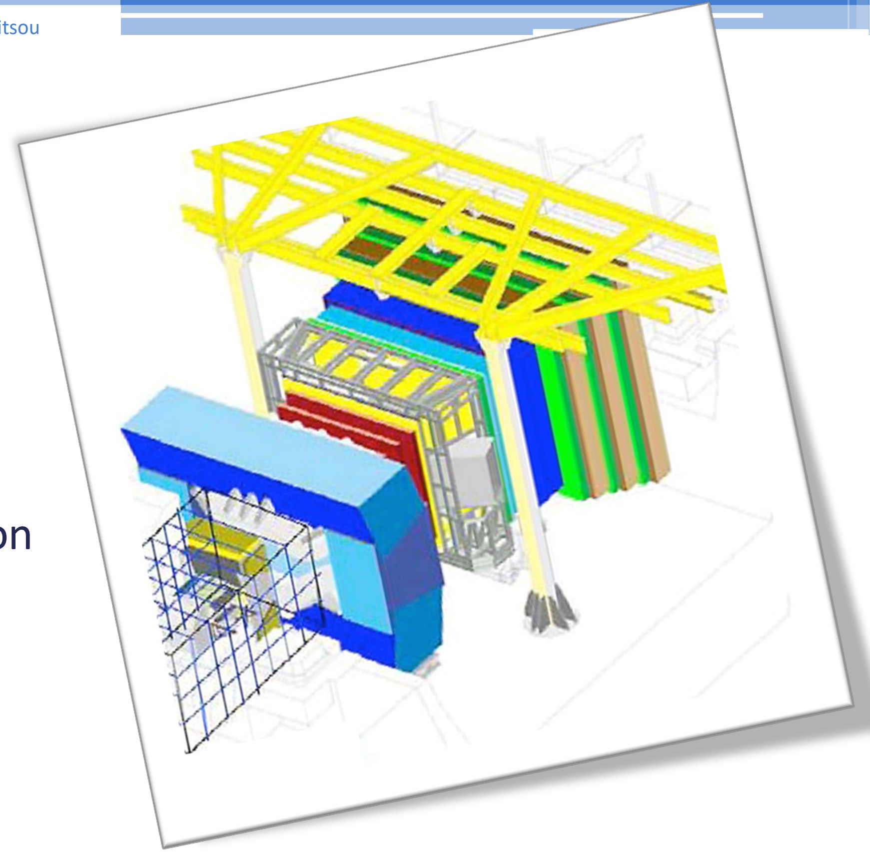
data / background

monopole signal

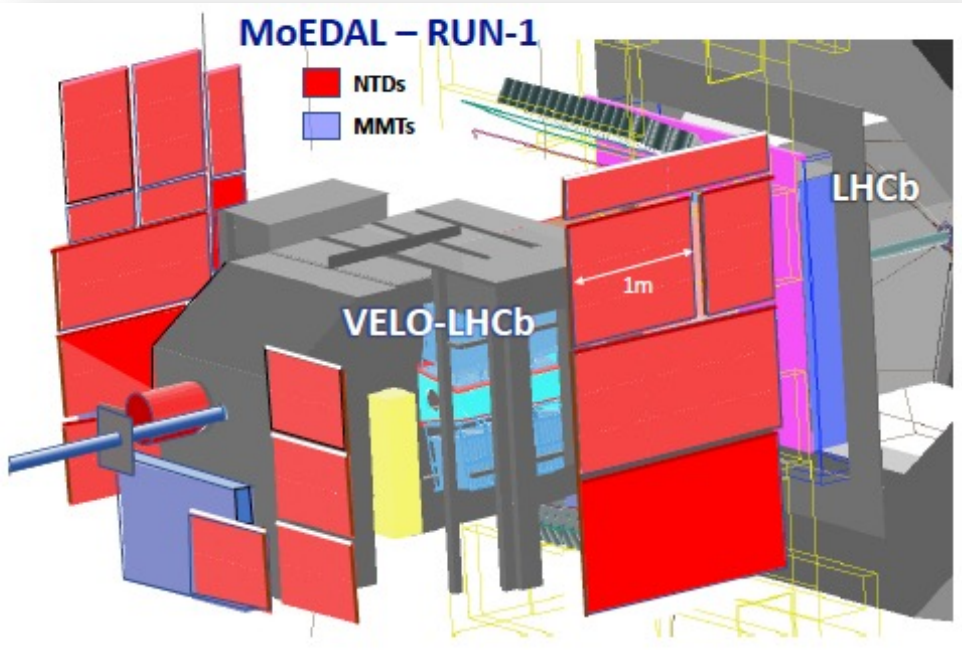
First ATLAS limits on γγ fusion production of monopoles and HECOs

MoEDAL results

- Magnetic monopoles – Drell-Yan & photon fusion
- Dyons
- Schwinger mechanism
- HECOs



MoEDAL – Monopole & Exotics Detector At LHC



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

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

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

MoEDAL

DETECTOR TECHNOLOGIES

① Nuclear Track Detectors (**NTD**)

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

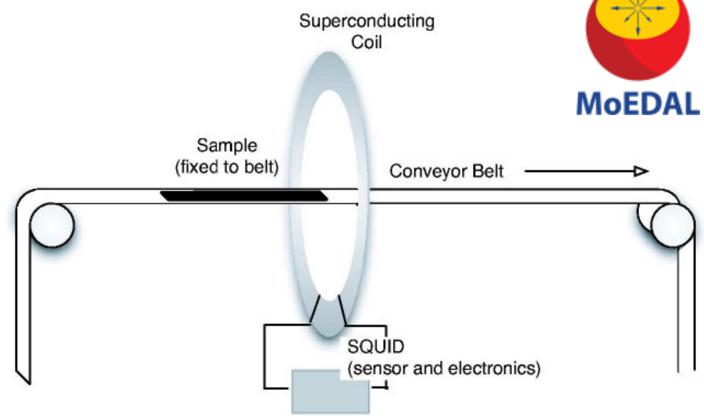
③ **TimePix** radiation background monitor

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

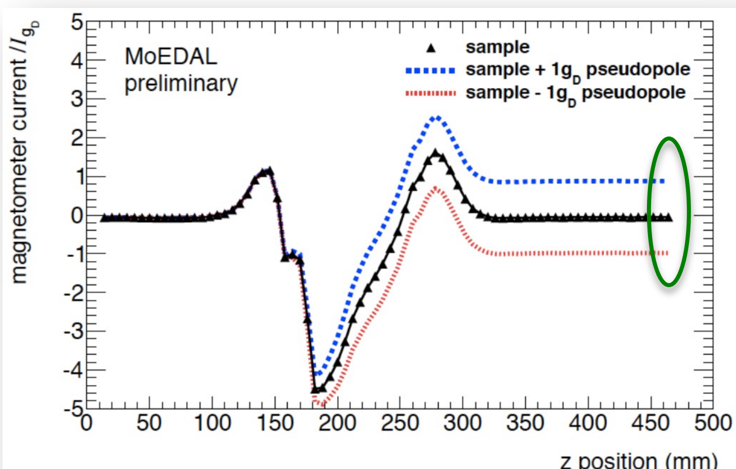
See also Jim Pinfold's talk

MMT scanning

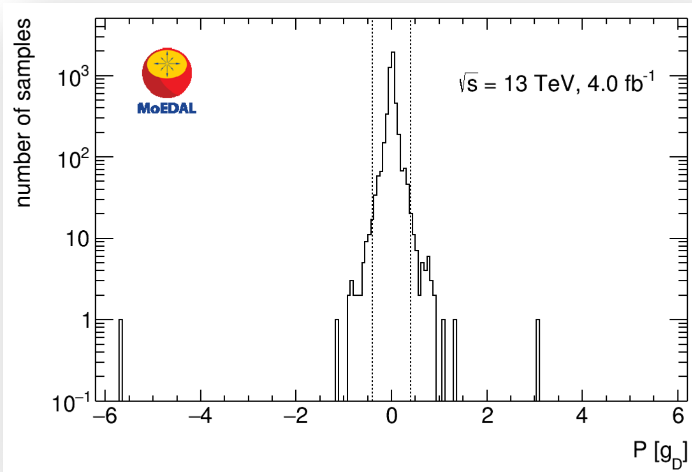
- Monopoles can bind to nuclei and get trapped
- MMTs analysed in superconducting quantum interference device (SQUID) at ETH Zurich
- **Persistent current:** difference between resulting current after and before
- Outliers are **scanned several times** further



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



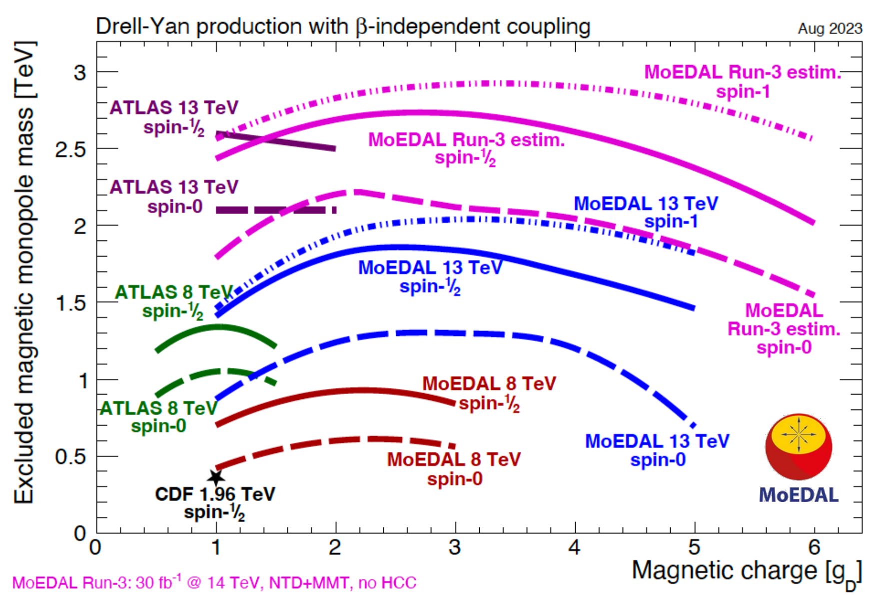
Calibration: Typical sample & pseudo-monopole curves

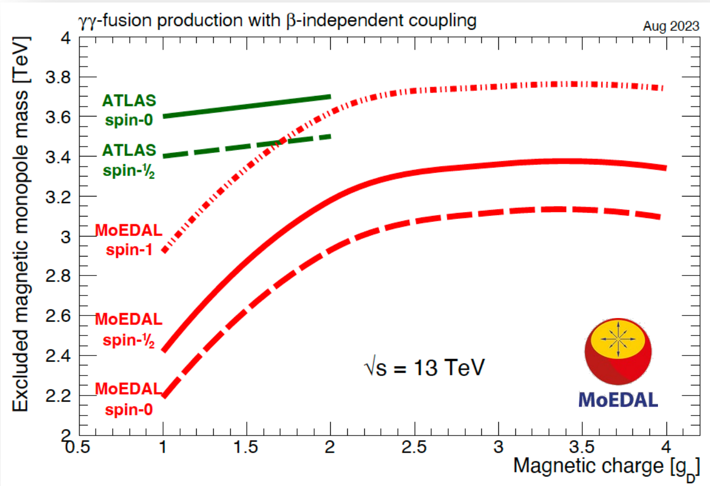


MoEDAL, PRL 123 (2019) 021802

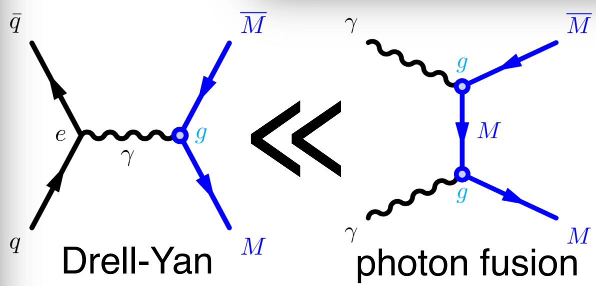
Magnetic monopole limits

- Novelties in monopole models: β-dependent coupling, spin-1 monopoles, γγ fusion
- MoEDAL set world-best collider limits for **|g| > 2 g_D**
- ATLAS set best limits for **|g| ≤ 2 g_D**





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]

Mass limits extracted with Feynman-*like* diagrams that **ignore non-perturbativity of large monopole-photon coupling**

Dyons: electric & magnetic charge

MoEDAL

Science 165 (1969) 757

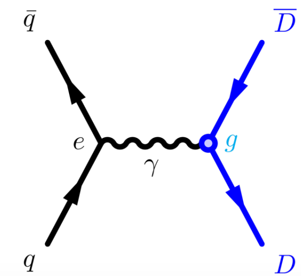
A Magnetic Model of Matter

A speculation probes deep within the structure of nuclear particles and predicts a new form of matter.

Julian Schwinger

SCIENCE

- Predicted in GUT theories, string theories, …
- MoEDAL MMT scanning searching for captured dyons



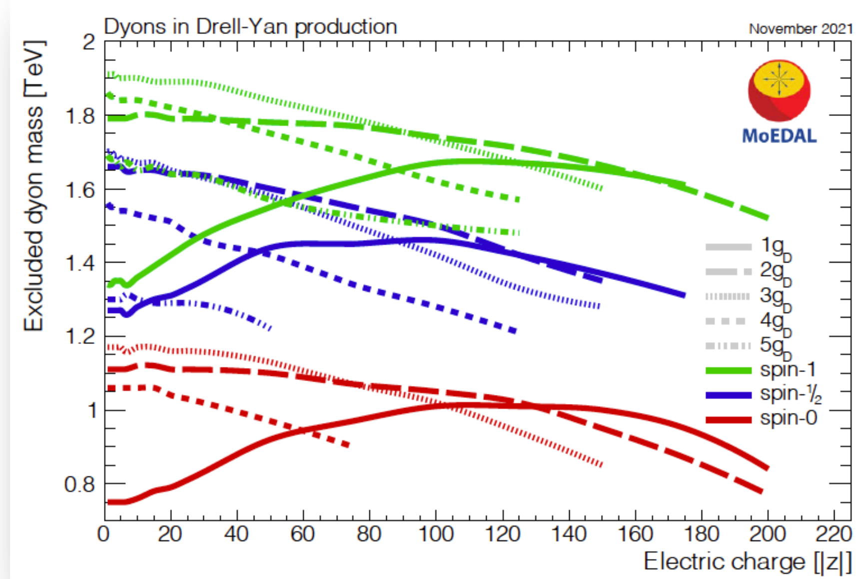
First explicit accelerator search for direct dyon production!

ABOUT NEWS

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

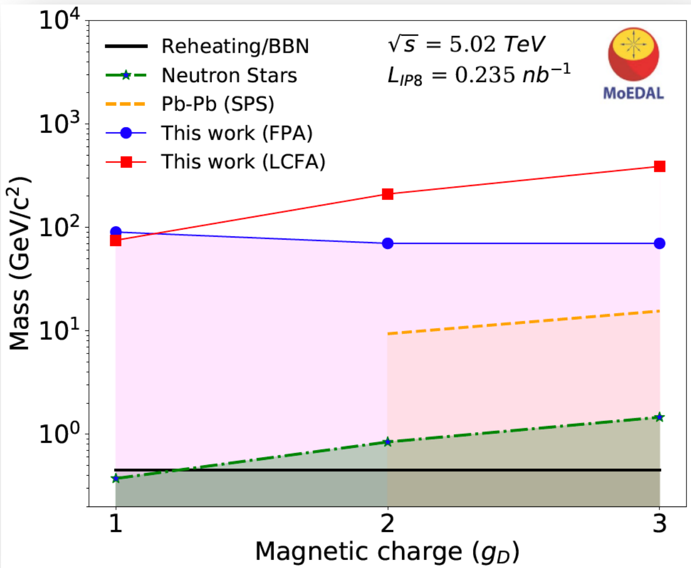
17 FEBRUARY, 2020 | By Ana Lopes

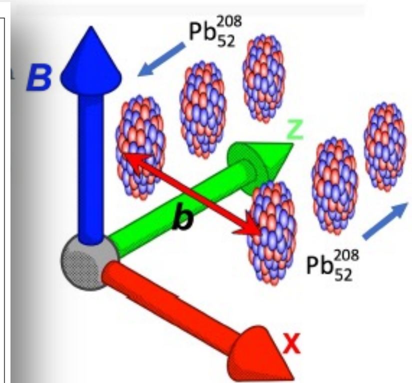


MoEDAL, PRL 126 (2021) 071801

Monopoles via thermal Schwinger mechanism

MoEDAL

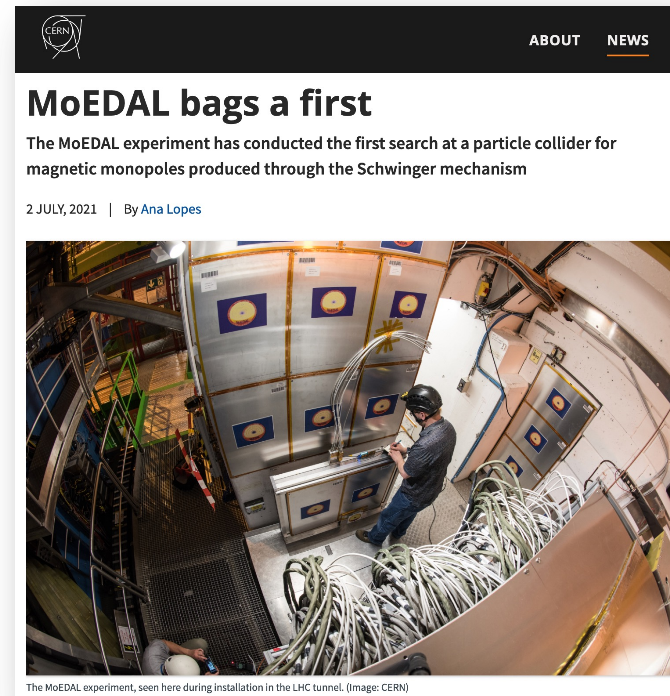




Monopole-antimonopole pairs may be produced in strong magnetic fields present in heavy-ion collisions

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

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



ABOUT NEWS

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

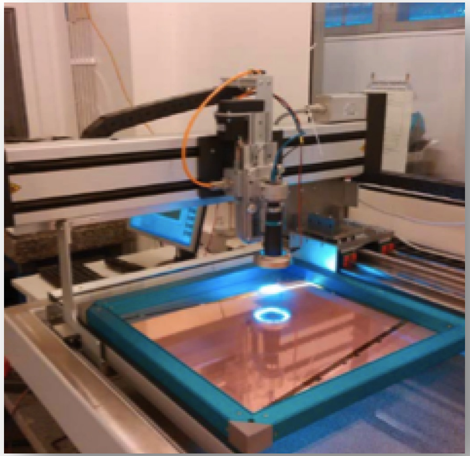
The MoEDAL experiment, seen here during installation in the LHC tunnel. (Image: CERN)

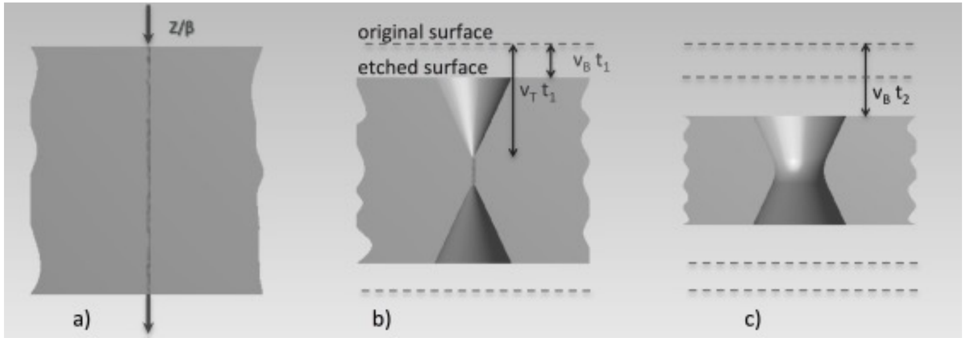
MoEDAL, Nature 602 (2022) 7895, 63-67

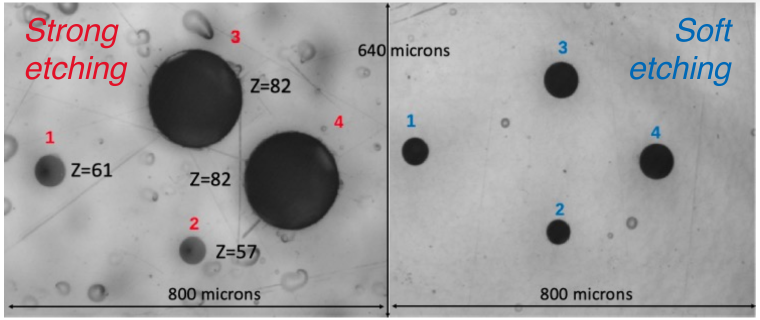
NTD analysis

MoEDAL

- Passage of HIP through plastic NTD marked by *invisible* damage zone (**“latent track”**) along the trajectory
- Damage zone revealed as a **cone-shaped etch-pit** when plastic sheet **chemically etched →** in ethyl alcohol solution in INFN Bologna
- NTDs **scanned** to detect etch-pits with automatic scanning system
- Scanning efficiency for detection above threshold is **>99%**







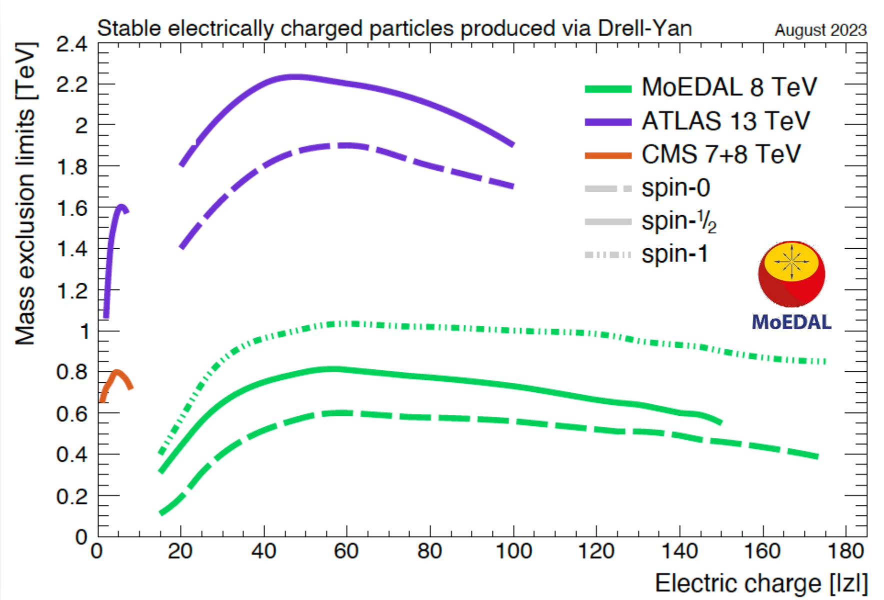
Calibration with Pb^{82+} and Xe^{54+} ion beams

No candidates found in the stacks examined

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 achieved in soon-to-be-released **Run 2 analysis**
  - higher c.m.s. energy: 13 TeV
  - larger integrated luminosity
  - larger exposed NTD surface
  - lower CR39 *Z/β* threshold than Macrofol



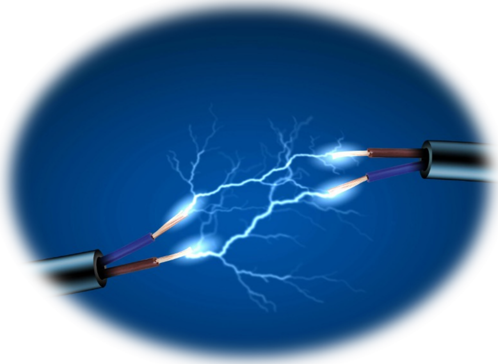
Non-perturbativity of large coupling can be tackled by appropriate **resummation** [Alexandre, Mavromatos, Musumeci, VAM, *LHCP2023 & paper in preparation*]

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

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

Prospects for 'low' electric charges

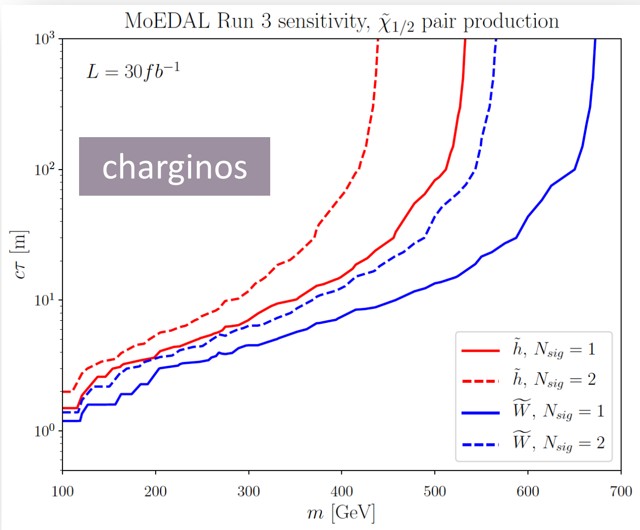
- Supersymmetric long-lived particles
- Charges ~1*e* – 10*e*



shutterstock.com

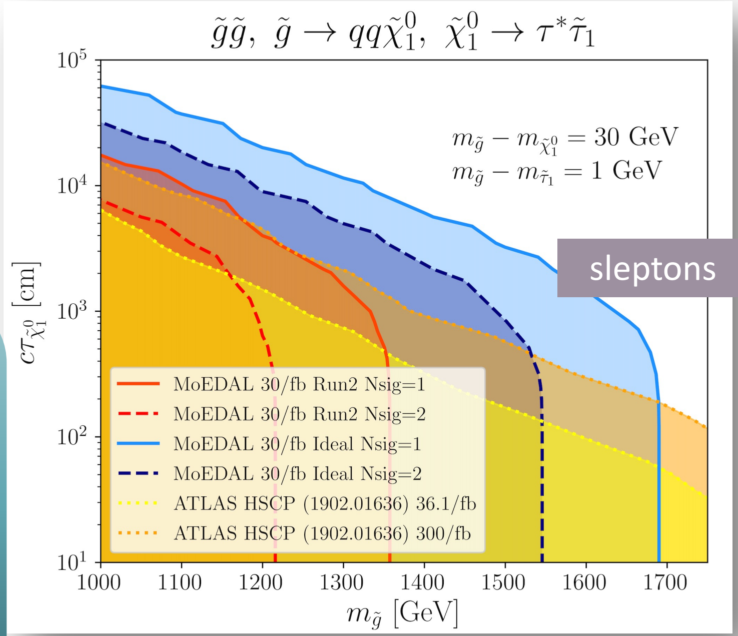
Long-lived SUSY partners in MoEDAL

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



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

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



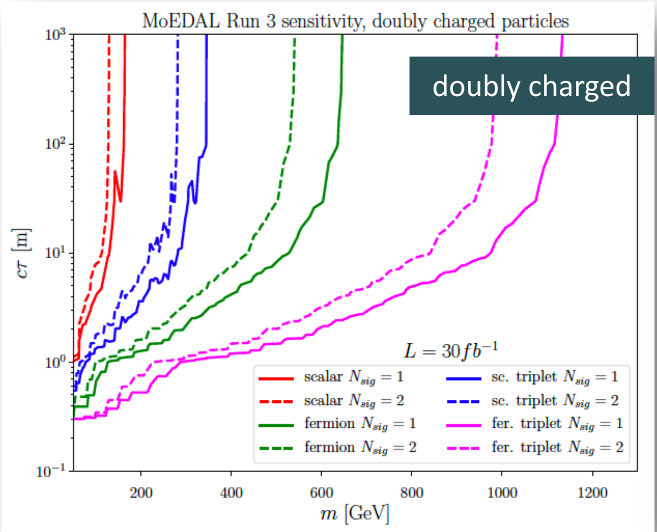
Felea, VAM *et al*, EPJC 80 (2020) 431

Study comparing MoEDAL vs. CMS:
Sakurai, VAM *et al*, J.Phys.Conf.Series 1586 (2020) 012018

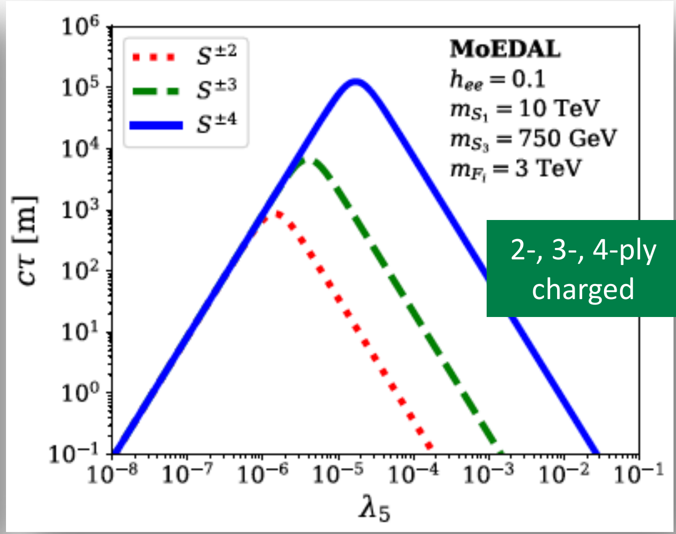
Multiply charged particles – model-specific

- 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 some radiative 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



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

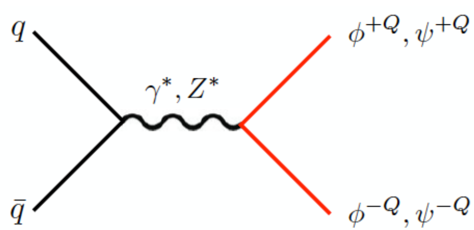


Hirsch *et al*, EPJC 81 (2021) 697

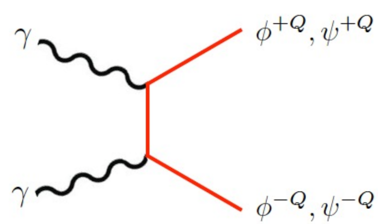
Multiply charged particles – generic case

- 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

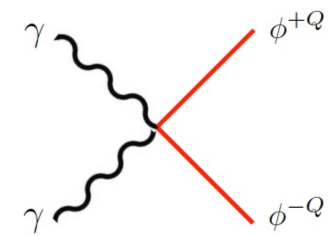
SU(2) singlet	color singlet	color triplet
spin 0	colorless scalar	colored scalar
spin 1/2	colorless fermion	colored fermion



s-channel (Drell-Yan)

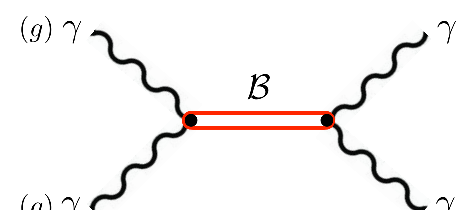


t-channel γγ fusion



seagull γγ fusion (scalar only)

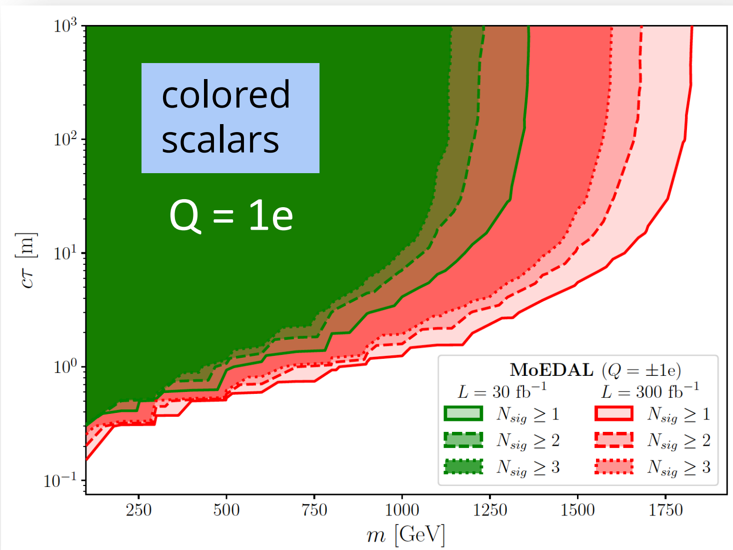
- Production of a bound state is considered
  - constrained by ATLAS and CMS searches for diphoton events
    - not relevant for MoEDAL



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

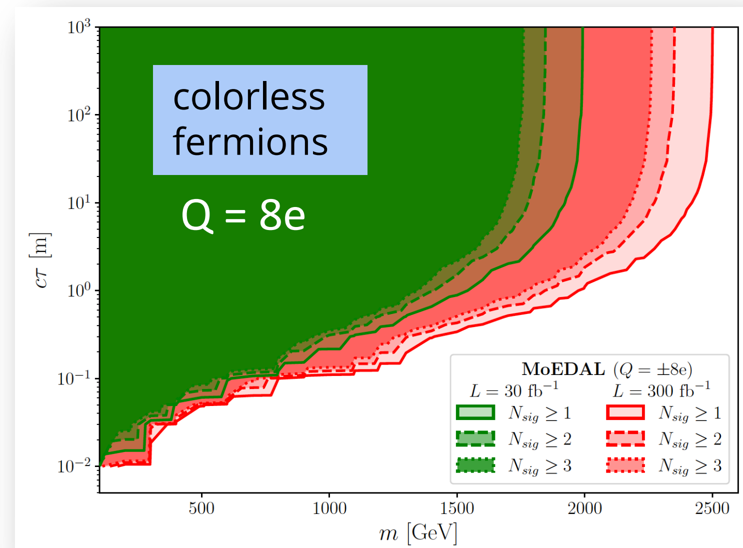
MoEDAL reach

- Singly charged colorless scalars only observable at HL-LHC
- MoEDAL sensitivity to colored scalars similar to colored fermions
- For high charges up to 8*e* good sensitivity expected from MoEDAL even in Run 3



Run 3
Masses up to 2 TeV can be probed

HL-LHC
Masses up to 2.5 TeV can be probed



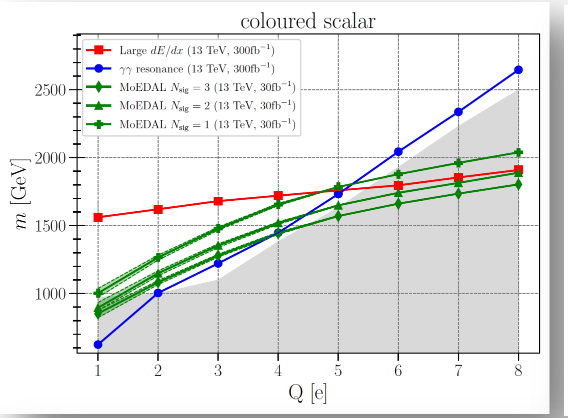
Altakach, Lamba, Masełek, VAM, Sakurai, [EPJC 82 (2022) 848]

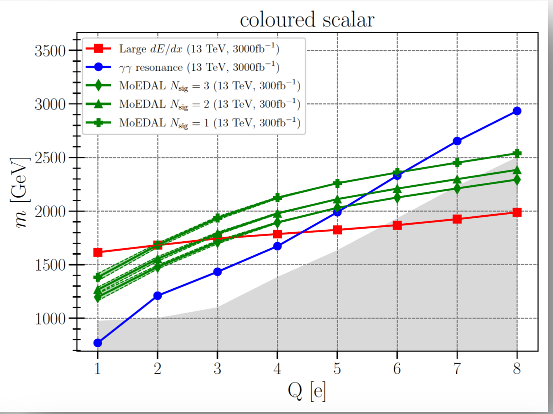
MoEDAL vs. ATLAS/CMS

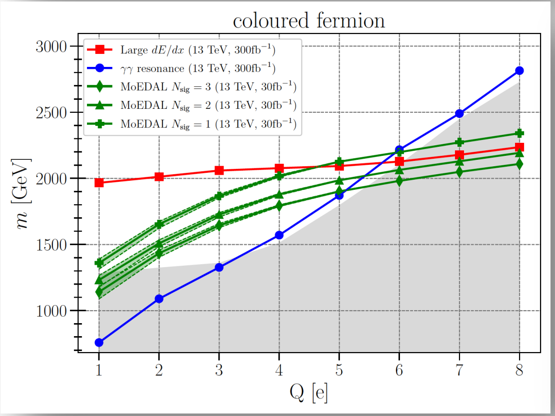
- Grey region excluded by ATLAS/CMS Run 1 / Run 2 searches
- ATLAS/CMS direct detection based on searches for large *dE/dx* → better sensitivity at low charges
- ATLAS/CMS searches for diphoton resonances offer better coverage at high charges
- **MoEDAL has the best sensitivity at intermediate electric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

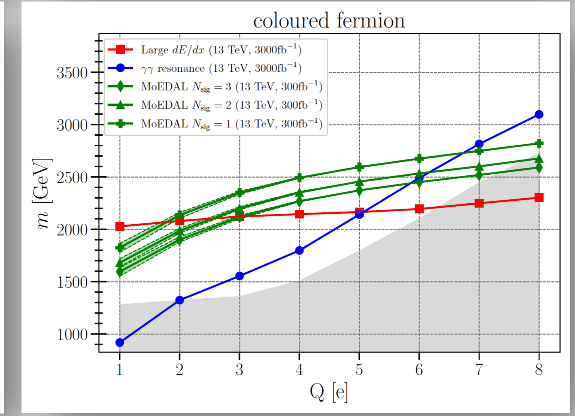
Run 3

HL-LHC









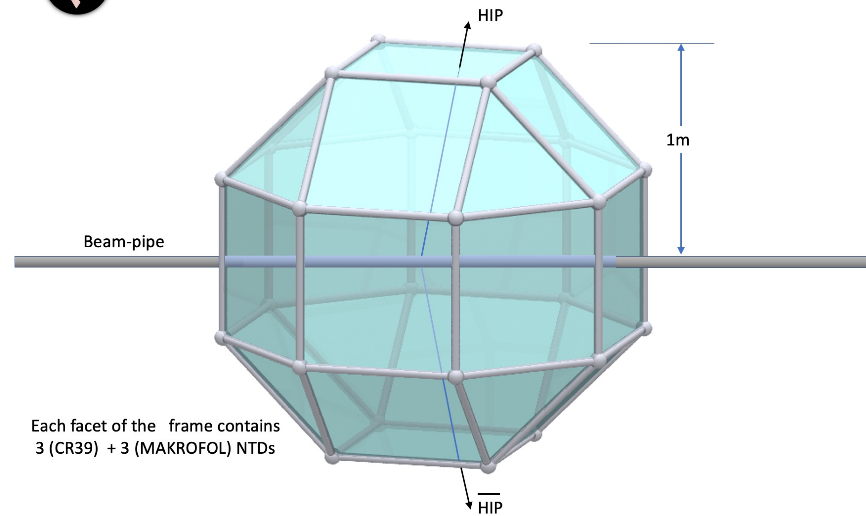
Altakach, Lamba, Masełek, VAM, Sakurai, EPJC 82 (2022) 848

Beyond LHC: MEDICI @ FCC-hh

- MoEDAL preliminary plans for MEDICI (Monopole and Exotics Detector Infrastructure for Colliding Ions)
- MEDICI HIP ➜ a polyhedral "ball" with radius 1 m sensitive to magnetic and electric charges
- Assuming 3 ab^{-1} and no intervening material, magnetic monopole masses up to **~25 TeV** can be reached

MoEDAL contribution to Snowmass, arXiv:2209.03988, EPJ-ST, *to appear*

FCC-hh: 100 TeV *pp* collisions



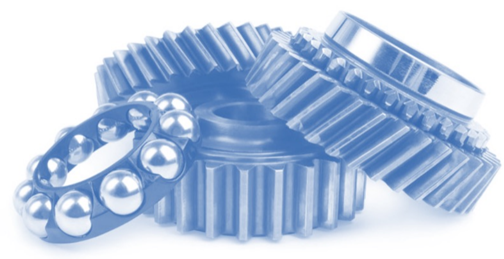
	Magnetic charge (g_D)					
	1	2	3	4	5	6
Spin	95% CL mass limits [TeV/c^2]					
0	14.9	17.0	18.2	19.1	19.8	20.3
1/2	20.0	22.4	23.7	24.7	25.5	26.1
1	20.5	22.7	23.9	24.8	25.5	26.1

Summary & outlook

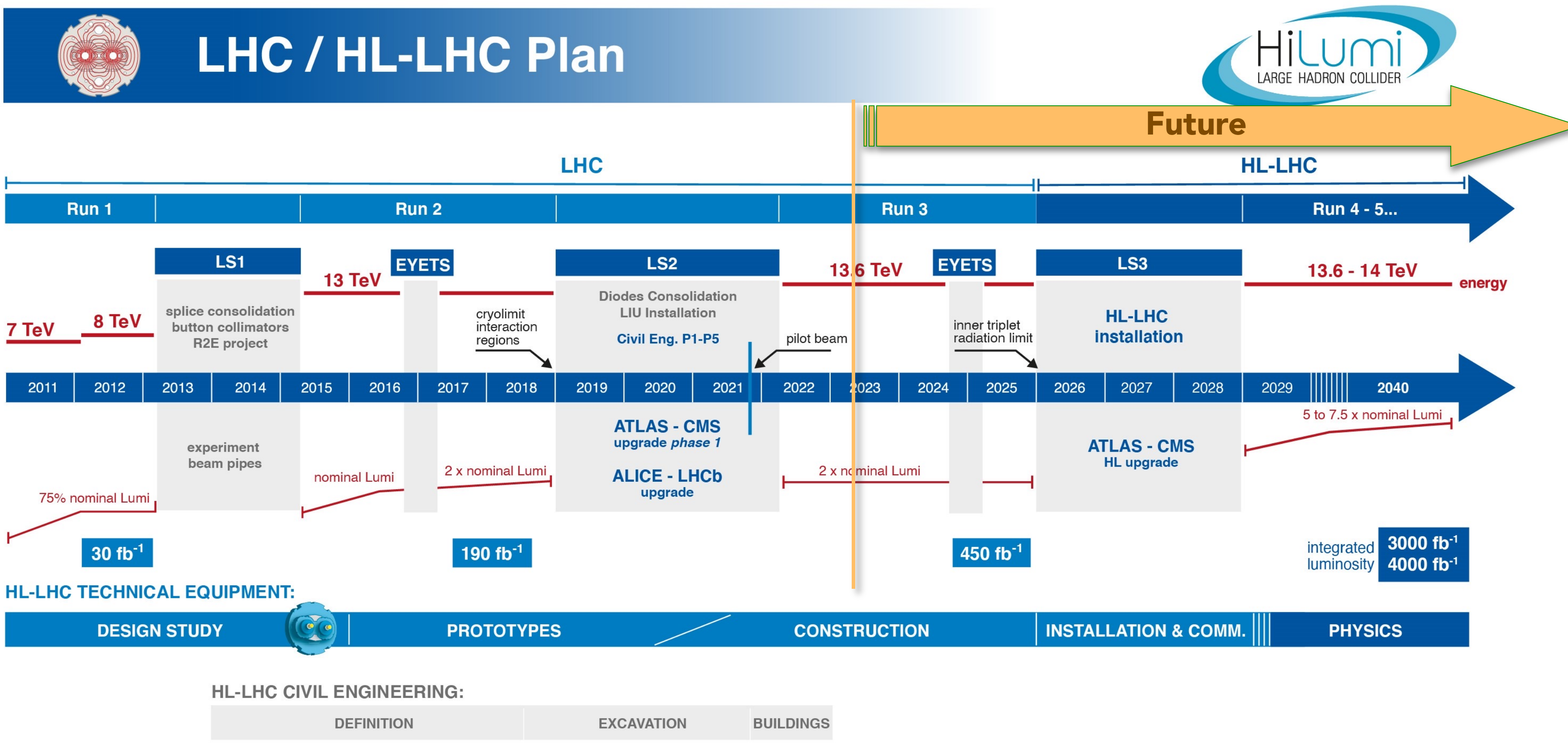
- Highly ionizing particles are predicted in various scenarios of New Physics
  - Single or multiple electric charges
  - Isolated magnetic charges
- Growing interest in searching for these states in collider experiments
  - Combining dE/dx and timing information
- ATLAS & MoEDAL work in complementary way towards this direction
- Several studies show promising prospects for experiments to explore charges $\leq 10e$ in future LHC runs
- Stay tuned for upcoming MoEDAL results!
  - Run-2 NTD analysis @ 13 TeV → improved sensitivity to electric charges
  - Magnetic monopoles in Schwinger mechanism probed in CMS Run-1 beam pipe

Thank you for your attention!

Spares



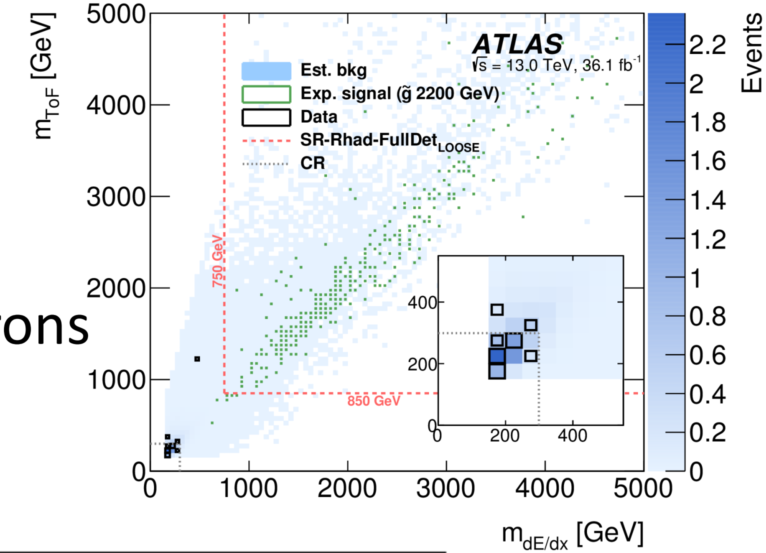
LHC & High Luminosity LHC (HL-LHC)



Heavy charged LL particles in ID+calo+MDT

- 36 fb^{-1} of 13 TeV *pp* collisions
- Detectors
  - Pixel → dE/dx
  - Tile, MDT, RPC → ToF
- Combination of *dE/dx* and ToF for R-hadrons
- Stau SR based only on ToF

Phys. Rev. D 99 (2019) 092007



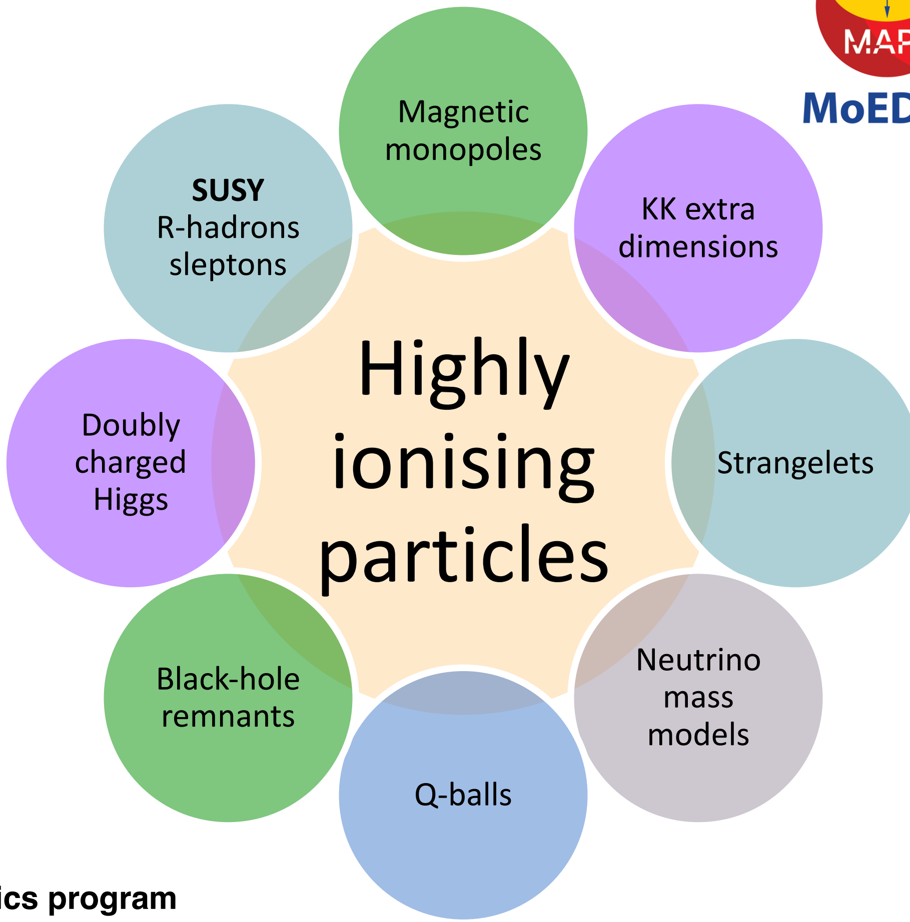
Signal region	Trigger	Candidate selection	Candidates per event	$\|\eta\|$	p [GeV]	β_{ToF}	$(\beta\gamma)_{dE/dx}$	Mass
SR-Rhad-MSagno	$E_{\mathrm{T}}^{\mathrm{miss}}$	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx
SR-Rhad-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	LOOSE	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.3	ToF & dE/dx
SR-Rhad-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx
SR-2Cand-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	LOOSE	$= 2$	≤ 2.00	≥ 100	≤ 0.95	-	ToF
SR-1Cand-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$	TIGHT	$= 1$	≤ 1.65	≥ 200	≤ 0.80	-	ToF

MoEDAL physics goals

MoEDAL

- 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

Results

MoEDAL

- 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

Run-2 MoEDAL deployment

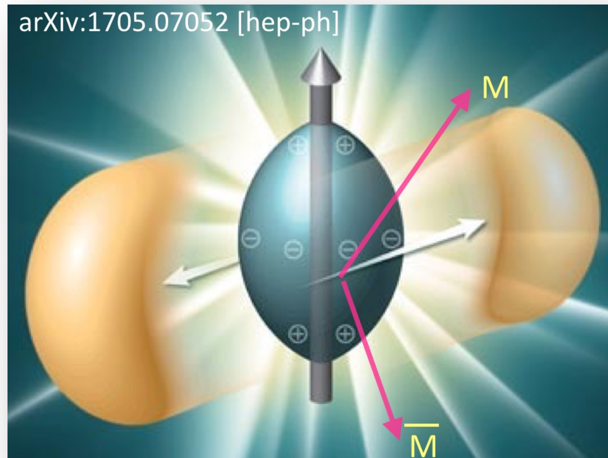
MMT
- Installed in forward region under beam pipe & in **sides**
- Approximately **800 kg** of Al
- Total 2400 aluminum bars

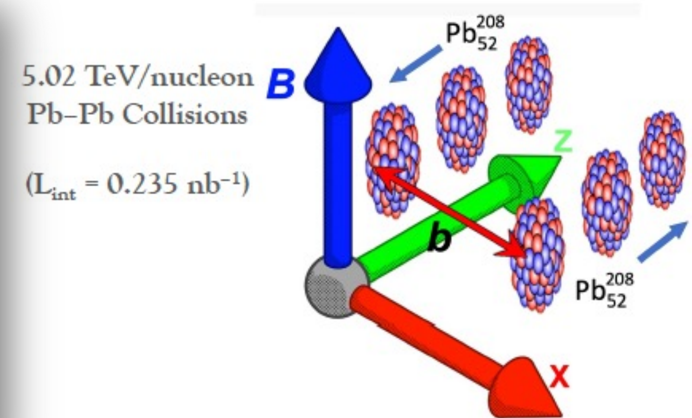
Low-threshold NTD
- Top of VELO cover
- Closest possible location to IP

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

Monopoles via thermal Schwinger mechanism

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





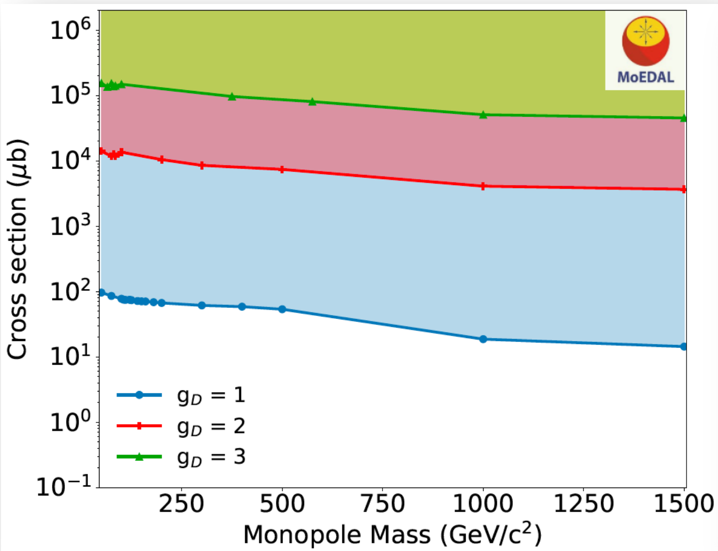
Advantages over DY & γγ-fusion production

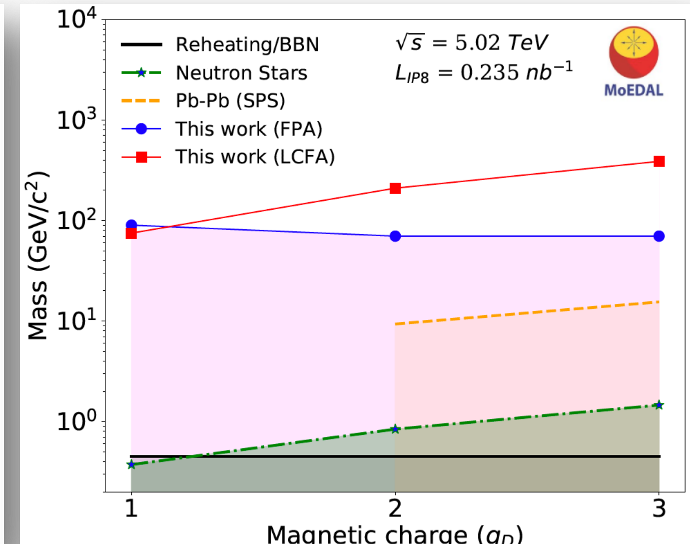
- cross-section calculation using semiclassical techniques ⇒ does not suffer from non-perturbative nature of coupling
- no exponential suppression $e^{-4/\alpha}$ for finite-sized monopoles

Gould, Ho, Rajantie, PRD 100, 015041 (2019), arXiv:2103.14454
Ho & Rajantie, PRD 101, 055003 (2020), PRD 103 (2021) 11, 115033

Schwinger production results

- Exposure of MMTs in 0.235 nb^{-1} of Pb-Pb heavy-ion collisions at 5.02 TeV per nucleon
- Limits on monopoles of 1 – 3 g_D and masses up to 75 GeV
- First limits from collider experiment based on non-perturbative calculation of monopole production cross section
- First direct search sensitive to monopoles that are not point-like





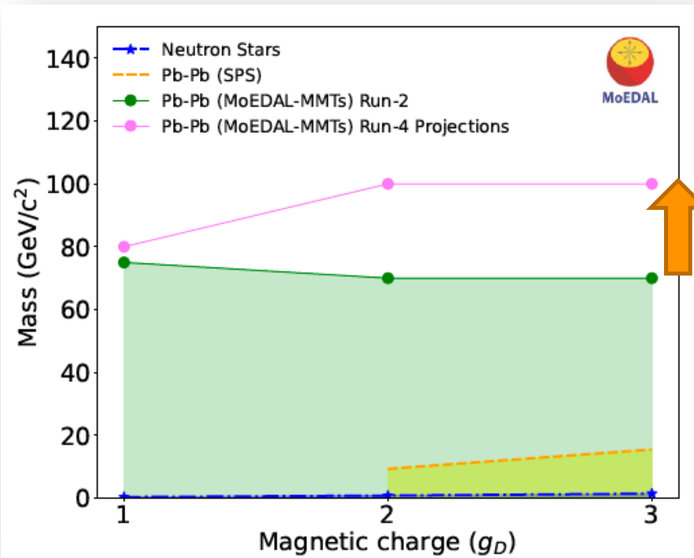
Monopole mass reach appears to be 20–30 times lower than current bounds from ATLAS and MoEDAL, however, this cross-section calculation is theoretically sound

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

Monopoles in Schwinger mechanism – Future

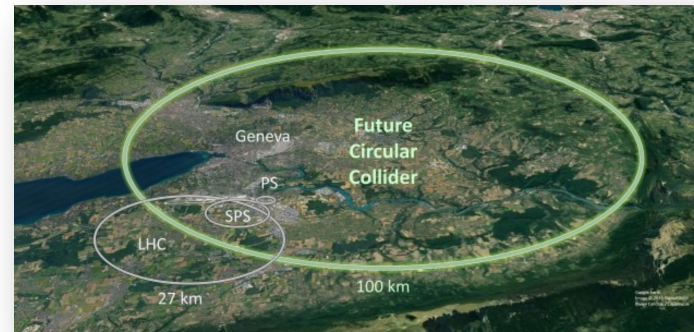
MoEDAL

- **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



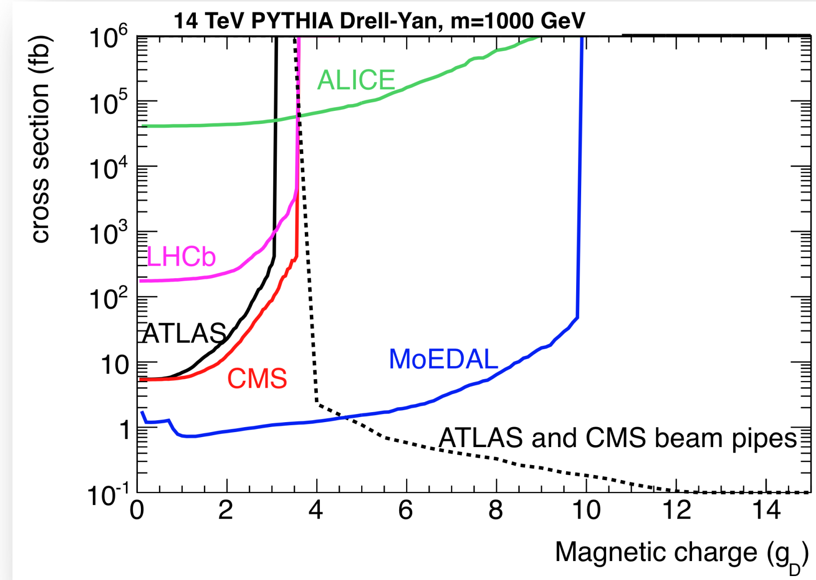
For FCC : $\sqrt{s_{NN}} \sim 40$ TeV
$\Rightarrow M \gtrsim 600$ GeV

Theoretical improvements in semiclassical and fully classical approaches

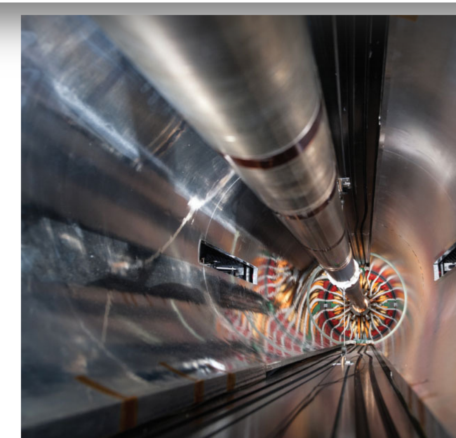
CMS beam pipe

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



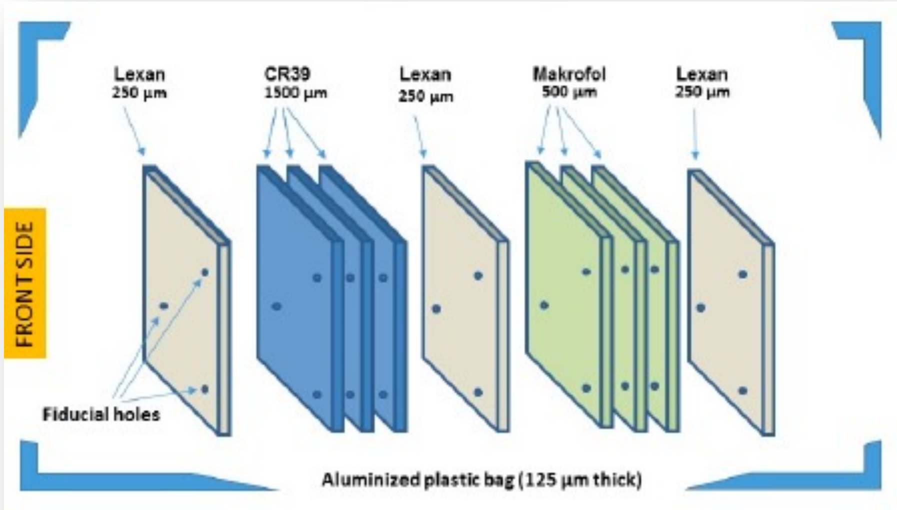
CERN Courier, Mar-Apr 2019

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

NTD+MMT search for HECOs and monopoles

Prototype NTD array of 125 × 25 cm × 25 cm stacks (7.8 m^2)

- 3 layers of CR39® polymer → low threshold z/β ~ 5 ⇒ time intensive analysis
- 3 layers of Makrofol DE® ☚ **used in analysis (less "visual noise"); threshold z/β ~ 50**
- 3 layers of Lexan® → protective layers only

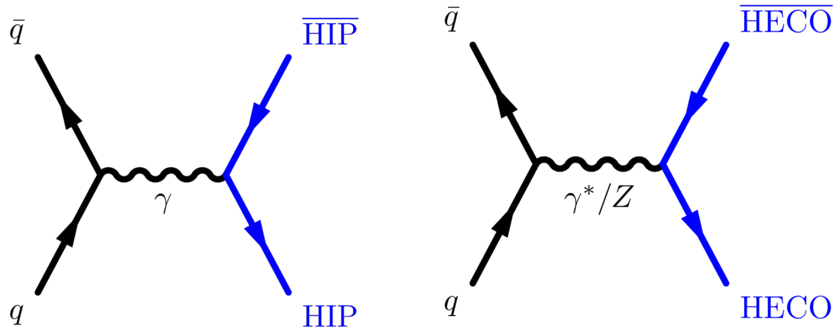


MoEDAL, arXiv:2112.05806 [hep-ex]

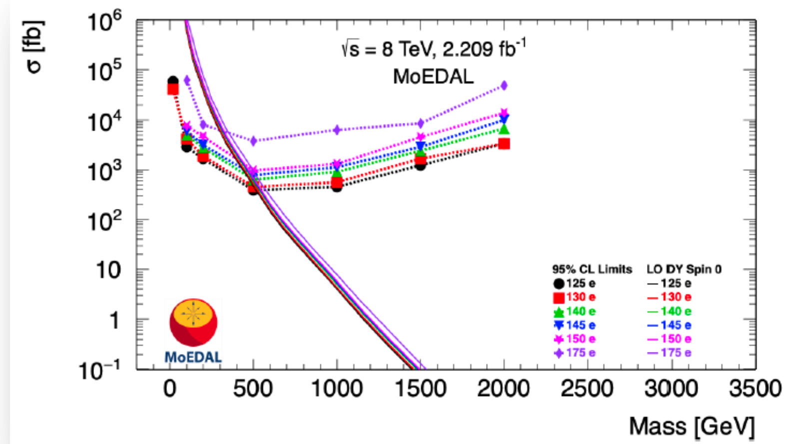
NTDs sheets kept in boxes mounted onto LHCb VELO alcove walls

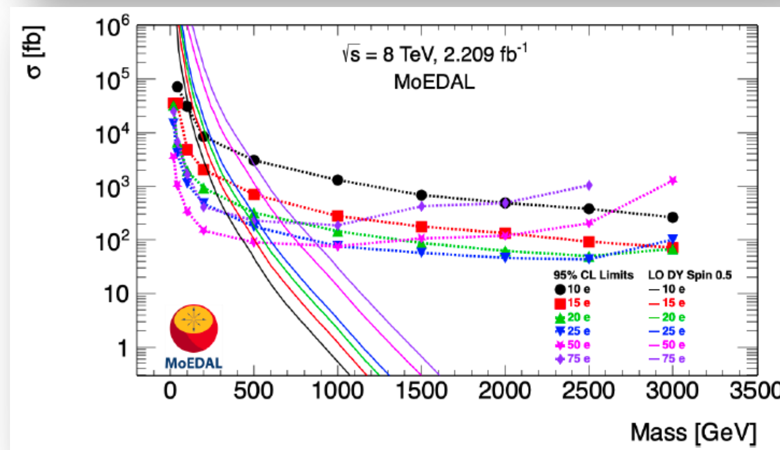
NTD results on HECOs

- 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, *in progress*]
- Limits set on HECO pairs with cross-sections from **~ 30 – 70 pb**

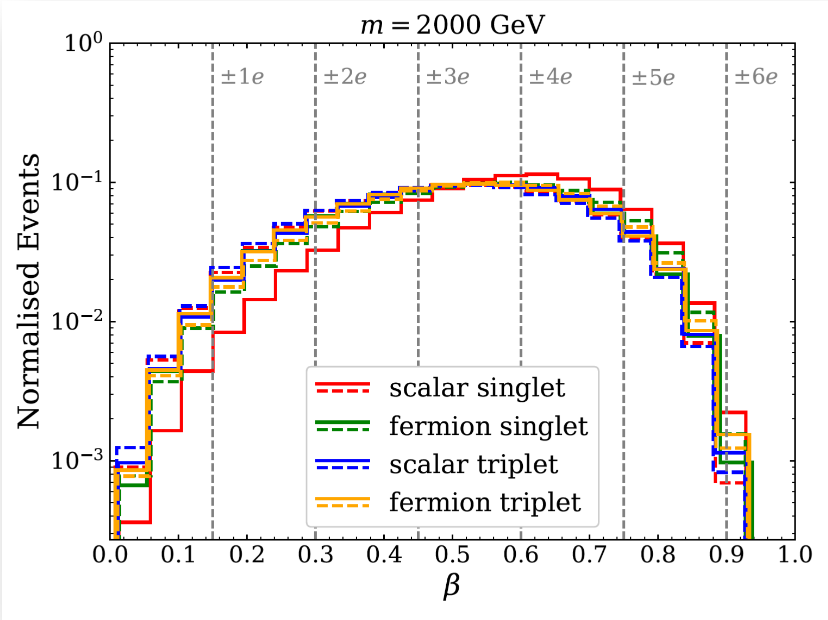




MoEDAL, arXiv:2112.05806 [hep-ex]

HIP kinematics

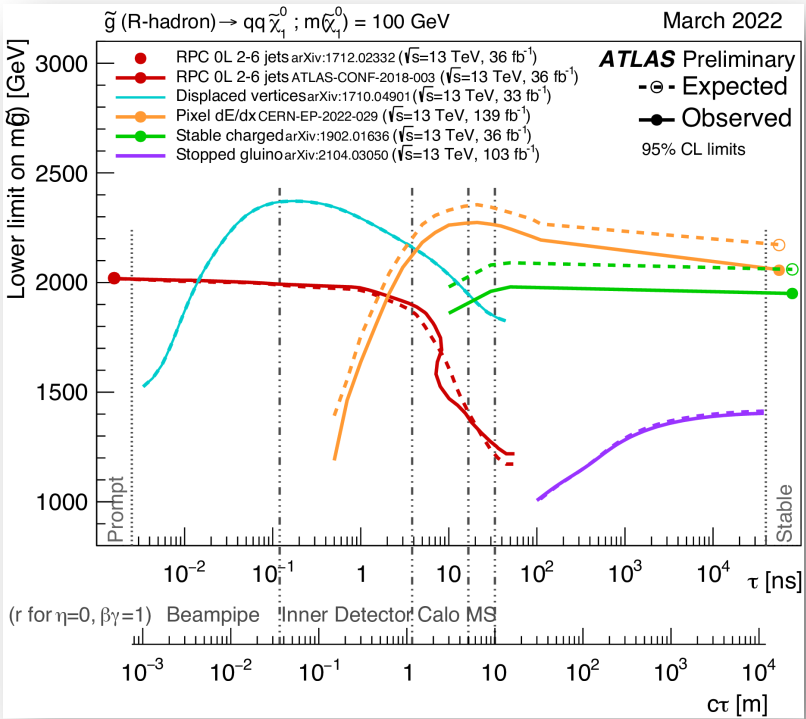
- MoEDAL NTDs sensitive to highly ionising particles with velocities $\beta < 0.15|Q|$
  - if sufficiently slow moving, even low charges may be detected
- Assumed to be "detector-stable", i.e. they decay after passing the whole detector volume
- MoEDAL is background-free experiment → discovery scenarios require 1, 2 or 3 signal events (N_{sig})
- Integrated luminosities at IP8 (LHCb/MoEDAL)
  - Run-3 → 30 fb^{-1}
  - High Luminosity LHC (HL-LHC) → 300 fb^{-1}
  - roughly 10 times less than ATLAS & CMS



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

Long-lived SUSY partners

- Supersymmetric charged long-lived 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 within correct bunch crossings
- Due to absence of **trigger, timing and SM backgrounds**, MoEDAL can *relax* selection requirements and increase sensitivity to charged long-lived SUSY particles



ATLAS, ATL-PHYS-PUB-2022-013