Searching for Magnetic Monopoles at the LHC and beyond

Igor Ostrovskiy (University of Alabama)

June 2024. IHEP, Beijing

Outline

- Magnetic Monopoles
- Searches at the LHC
  - MoEDAL Detector
  - Complementarity with ATLAS
  - Recent results
- Schwinger mechanism
  - First search
  - Most recent (Feb 2024) result
- Next frontier of monopole searches

Magnetic Monopoles

- Pierre Curie was the first to suggest that magnetic charges **could exist**

Séances de la Société Française de Physique (Paris), p76 (1894)

- In 1931 Paul Dirac showed that if *just one* magnetic monopole existed, then all electric charge in the universe **would be quantized**

*Proc. R. Soc. Lond. A **133**, 60 (1931)*

- In 1974 t'Hooft and, independently, Polyakov showed that *any* Grand Unified Theory (GUT) that incorporates electro-magnetism **contains magnetic monopole solutions**

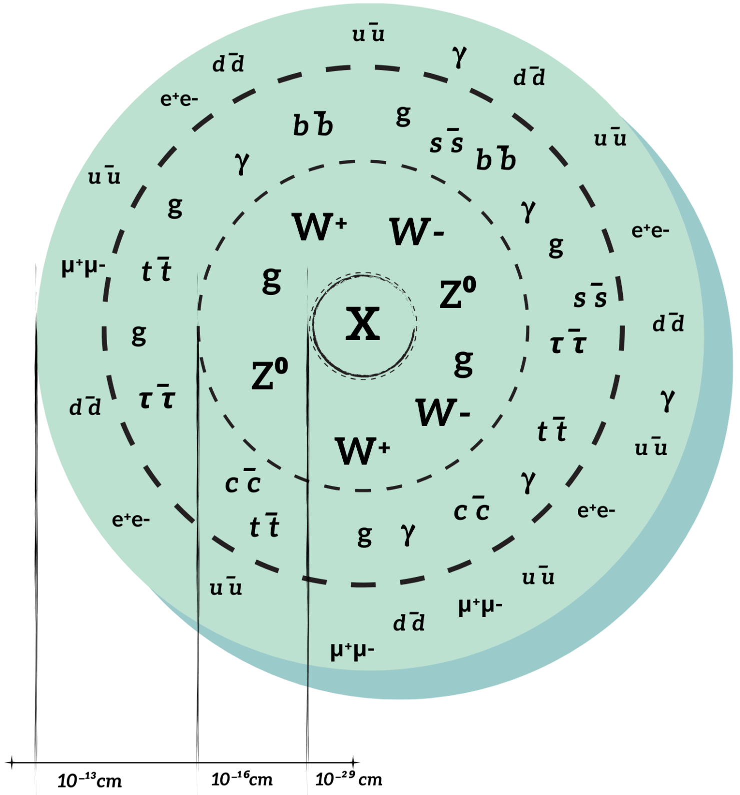
*Nucl. Phys. B **79**, 276 (1974); Письма в ЖЭТФ **20**, 430 (1974)*

- Mass is unknown. While the heavy GUT monopole (~10^{17} GeV) received the most interest earlier, several recent models point to possibility of monopoles with masses potentially **accessible at the LHC**

*Phys. Lett. B **391,** 360 (1997); EPJC **75**, 67 (2015); Phys. Lett. B **756,** 29 (2016); Phys. Rev. D **95**, 104025 (2017); EPJC **77**, 444 (2017); Phys. Rev. D **97**, 125010 (2018); Nucl. Phys. B **969** 115468 (2021)*

Magnetic Monopoles in GUT and SM

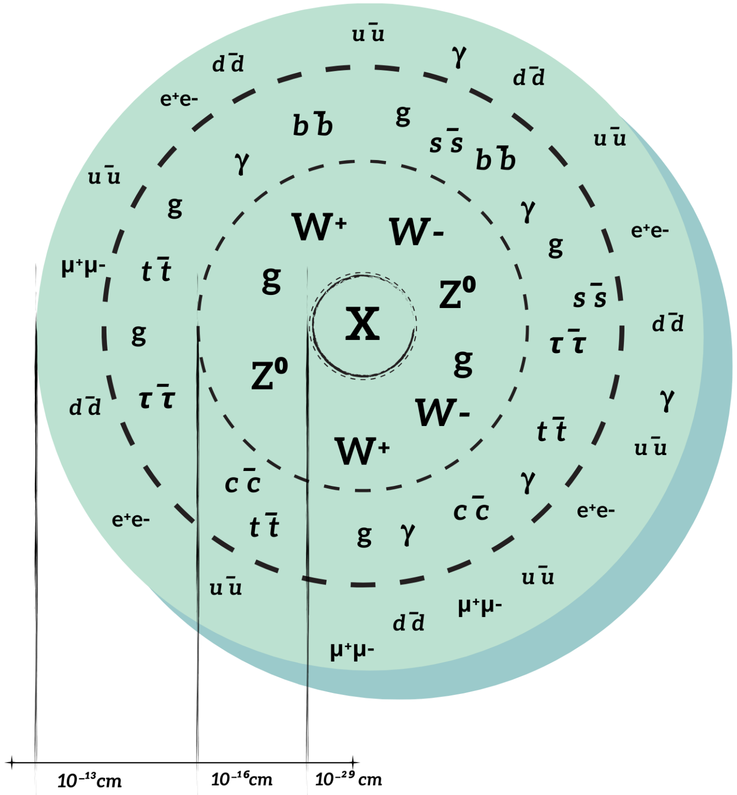
- When a simple Lie group is broken to a subgroup with a U(1) factor, the spectrum of states must include a topologically stable magnetic monopole
  - All GUT models that include E&M are thus predicting monopoles
- Mass is determined by the scale of the symmetry breaking and is ~10^{17} GeV for the SU(5) GUT, e.g., the Georgi–Glashow model
  - Such monopoles would overclose the universe! → the “monopole problem” that motivated the theory of inflation



The structure of a GUT monopole, a **composite object**. The three regions illustrate the Grand Unification, electroweak unification, and confinement regions

Magnetic Monopoles in GUT and SM

- SO(10) and others that break in several stages predict correspondingly **lighter poles** (IMMs), which would be produced **after inflation**
  - Of the models that are consistent with current proton decay limits, the Trinification suggests a monopole of a few TeV mass (K. Shafi)
- No stable solutions expected in SU(2) x U(1), i.e., the standard EW theory. However, Cho & Mason, and then many others (including J. Ellis), have found extensions of the SM that contain magnetic monopoles with **~TeV masses**



The structure of a GUT monopole, a **composite object**. The three regions illustrate the Grand Unification, electroweak unification, and confinement regions

Magnetic Monopole's basic properties

$e \cdot g_D = \frac{\hbar c}{2} n \rightarrow g_D = \frac{n}{2\alpha} e \Rightarrow$ $\mathbf{1 g_D = 68.5 \cdot e}$	• Depending on the model, the fundamental charge could be $g_M = 2, 3, \dots g_D$
$\frac{\boldsymbol{g_D^2}}{\boldsymbol{\hbar c}} \boldsymbol{\sim 34}$	• Perturbative field theory **does not apply**
$\boldsymbol{W \sim 2 \frac{MeV}{G \cdot m}}$	• IMMs in the galactic field and LHC monopoles will be **relativistic**
$-\frac{\boldsymbol{dE}}{\boldsymbol{dx}} \sim \frac{\boldsymbol{Z}}{\boldsymbol{A}} \boldsymbol{g_M^2} \cdot [\mathbf{ln}(\boldsymbol{\beta^2 \gamma^2}) + \dots]$	• Fast monopoles are highly ionizing! $\frac{dE}{dx} \sim g_M^2$= **4700 MIP** for $1 g_D$ • Ionization of g_M **increases with β**, as opposite to e

Magnetic Monopole searches

The relativistic quantum field theory of magnetic and electric charge is of such beauty that we must repeat after Dirac: “One would be surprised if Nature had made no use of it.”

Julian Schwinger, 1965

- Spurred by solid theoretical motivation, multitude of searches had been conducted in the decades starting from the late 60x
- Monopoles were searched at accelerators, cosmic rays, deep-sea sediments, moon rocks, and more
- Many detection techniques took advantage of large expected ionization – nuclear track detectors, scintillators; but the most direct probe of magnetic charge is via induction (SQUID magnetometer)
- This talk can not possibly do justice to all the searches, so will just highlight some select efforts

PHYSICAL REVIEW D VOLUME 4, NUMBER 5 1 SEPTEMBER 1971

Search for Magnetic Monopoles*

Henry H. Kolm
Francis Bitter National Magnet Laboratory,† Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

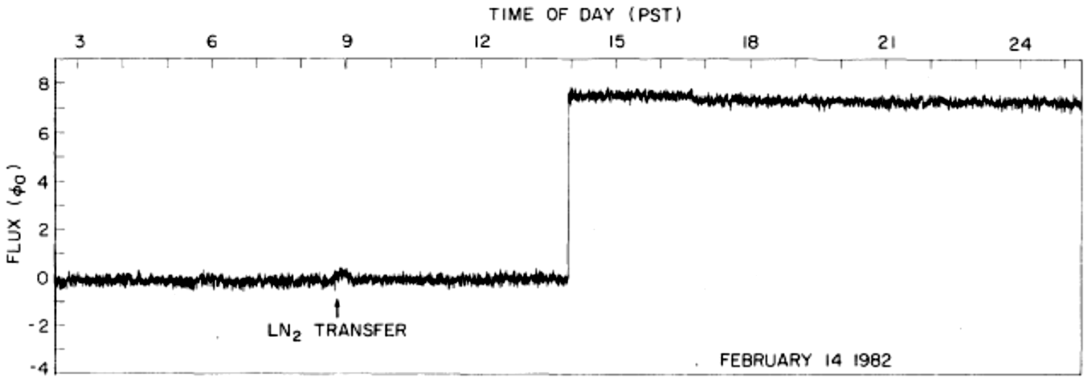
Francesco Villa and Allen Odian !
Stanford Linear Accelerator Center,‡ Stanford University, Stanford, California 94305

(Received 3 March 1971)

Magnetic Monopole searches

The Cabrera's event, 1982

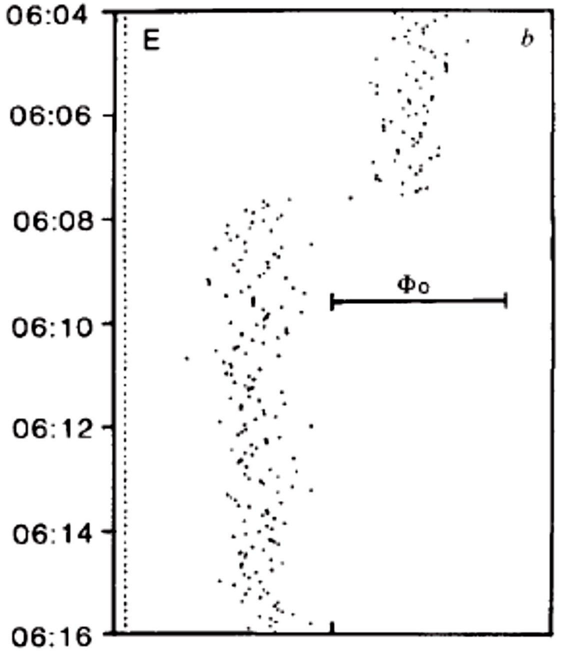
20 cm², induction (SQUID)



Phys. Rev. Lett. ***48****, 1378–1381 (1982)*

Imperial College event, 1985

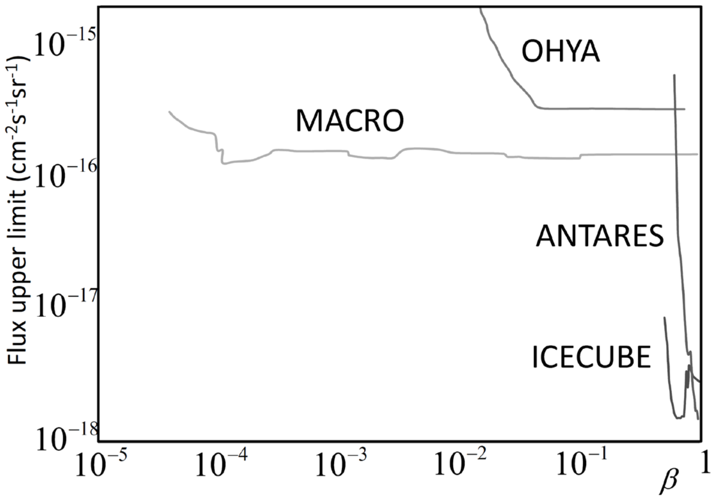
0.18 m², induction (SQUID)



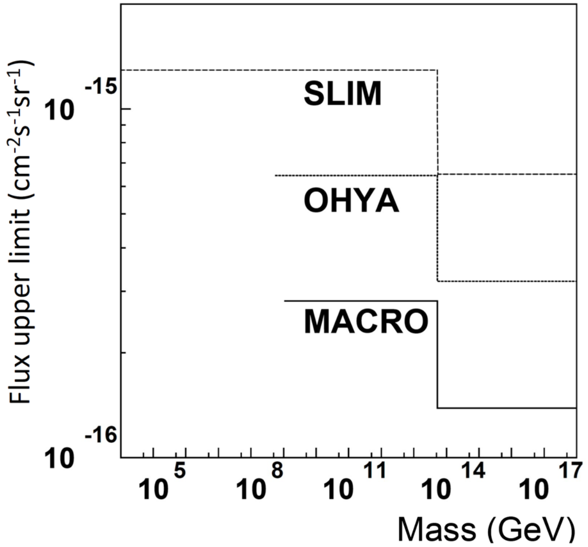
Nature ***321****, 402 - 406 (1986)*

Magnetic monopole searches

- MACRO
  - dE/dX (**NTDs**, scint., str.tubes)
  - **~10000 m^2**
- SLIM
  - dE/dX (**NTDs**)
  - ~5 km asl
  - **~400 m^2**
- Last cosmic ray searches have just peaked into interesting parameter space – below the **Parker bound**
- To probe lower-mass IMMs one needs to go to high elevations, so there is still a **wide gap of unprobed masses** between accelerator and cosmic ray experiments
- Several searches not shown due to explicit (NOvA) or implicit (IceCube, Anita-II) insensitivity to low-interm. masses

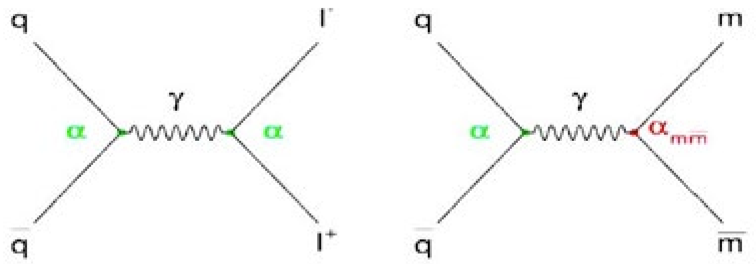


Particle Data Group review (2023)

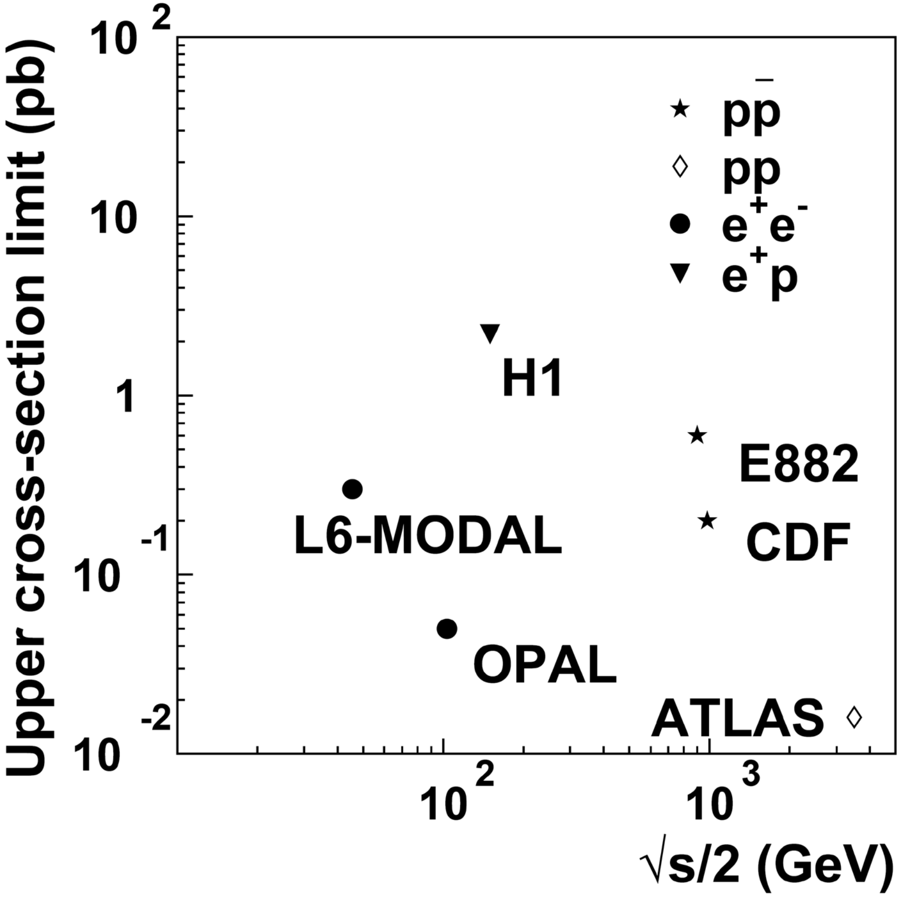


Magnetic monopole searches

- p/p, e-/p, e-/e+, p/p+ colliders – all searched for magnetic monopoles, both directly and indirectly
- Rates and kinematics are hard to calculate, as the coupling constant >>1
- To minimize model dependencies, compare results on cross-section limits vs. half the center-of-mass collision energy

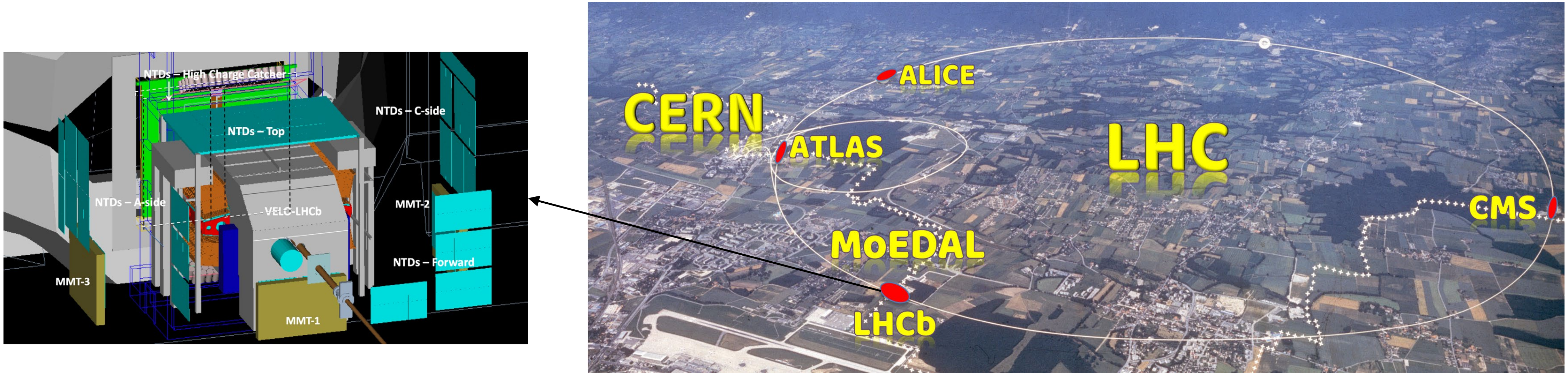


Drell-Yan production



Particle Data Group review (2016)

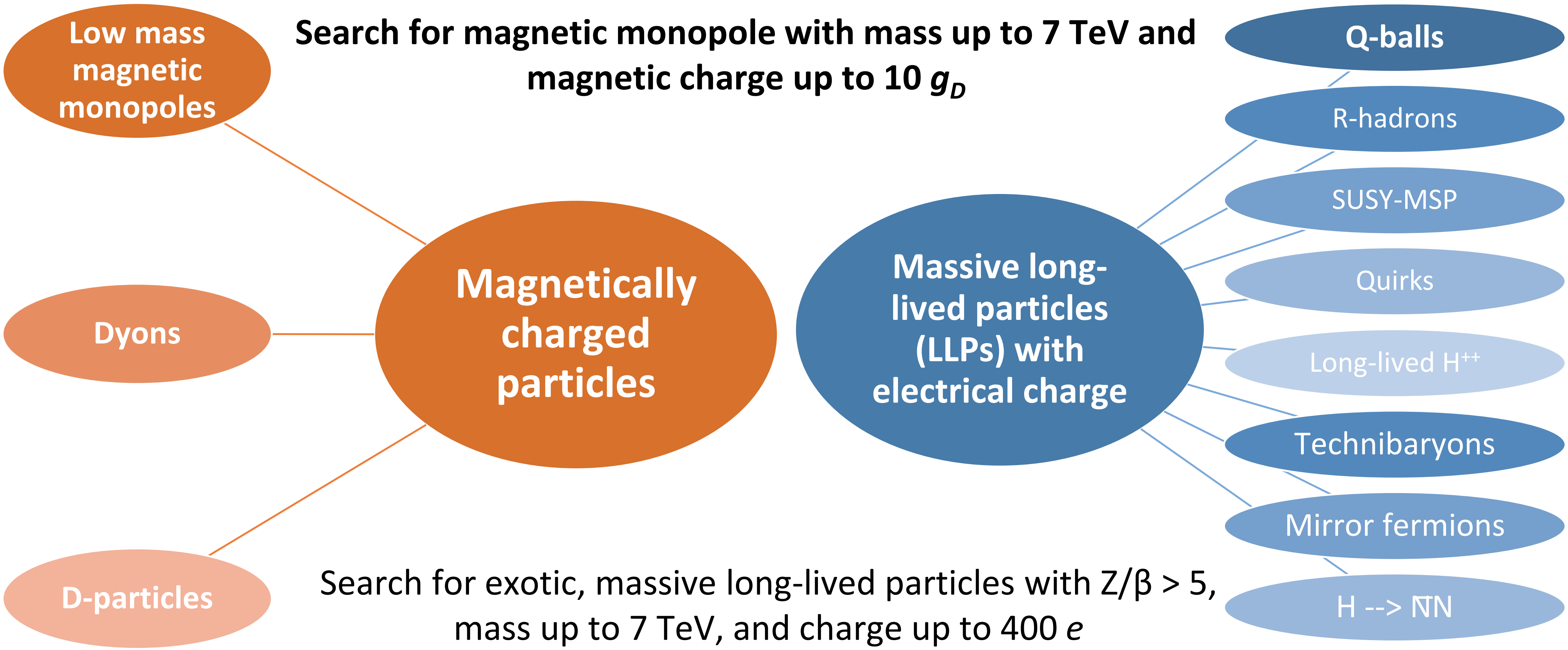
MoEDAL – dedicated search at the LHC



- "Monopole and other Exotics Detector At LHC" optimized to search fo **magnetic monopoles** and other highly ionizing particles with magnetic and/or electric charge (dyons, nuclearites, Q-balls,)
- ~70 physicists from >20 institutions from 7 countries. Approved by CERN 2009, started data-taking Spring 2015
- Deployed at IP8 in the **LHCb's VELO** cavern. Uses nuclear track detectors (**NTDs**), trapping volumes (**MMTs**) and TimePix detectors
- **World-leading limits** on $g > 2g_D$ monopole production in p-p collisions

MoEDAL's physics program, before Run-3

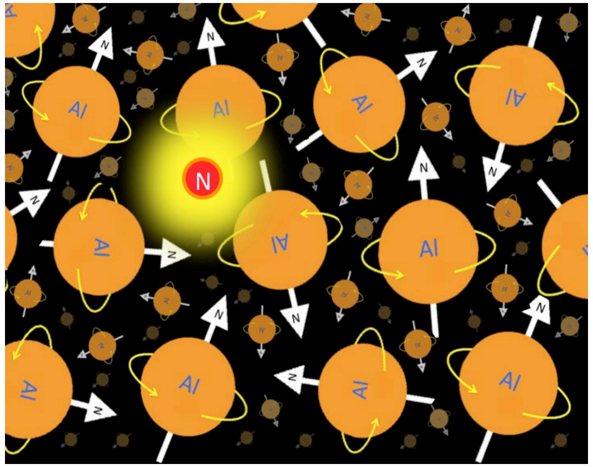
Search for magnetic monopole with mass up to 7 TeV and magnetic charge up to 10 g_D

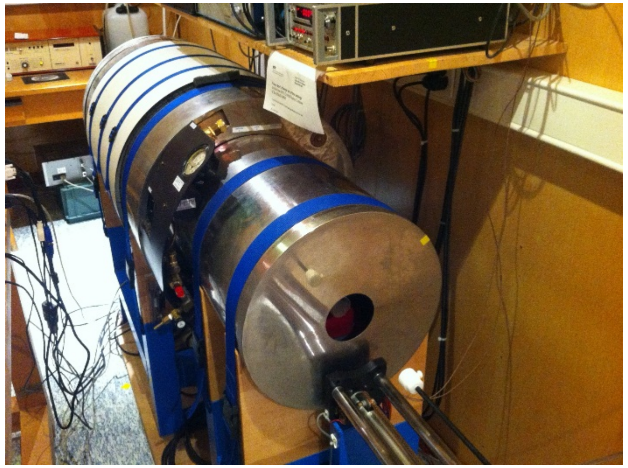


Search for exotic, massive long-lived particles with Z/β > 5, mass up to 7 TeV, and charge up to 400 *e*

Int.J.Mod.Phys. A ***29****, 1430050 (2014)*

Main sub-detector systems: MMTs

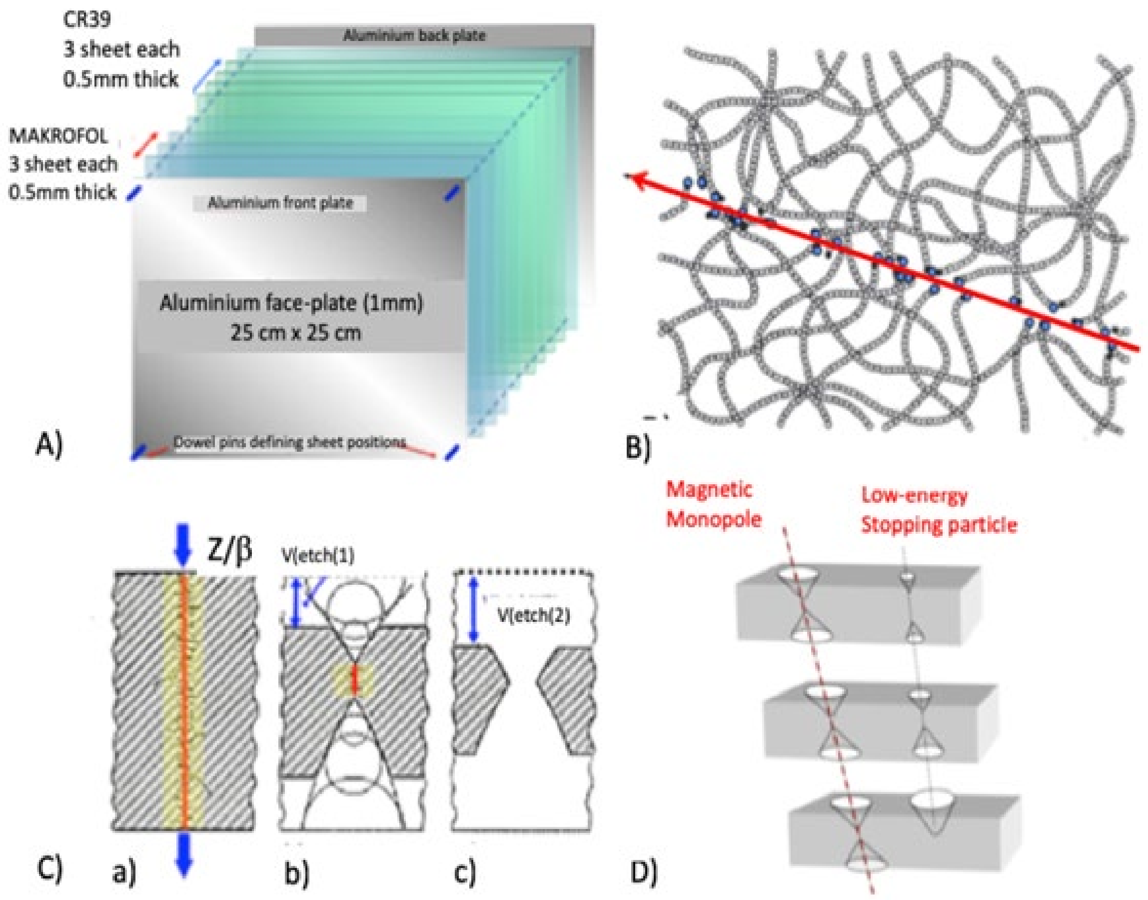


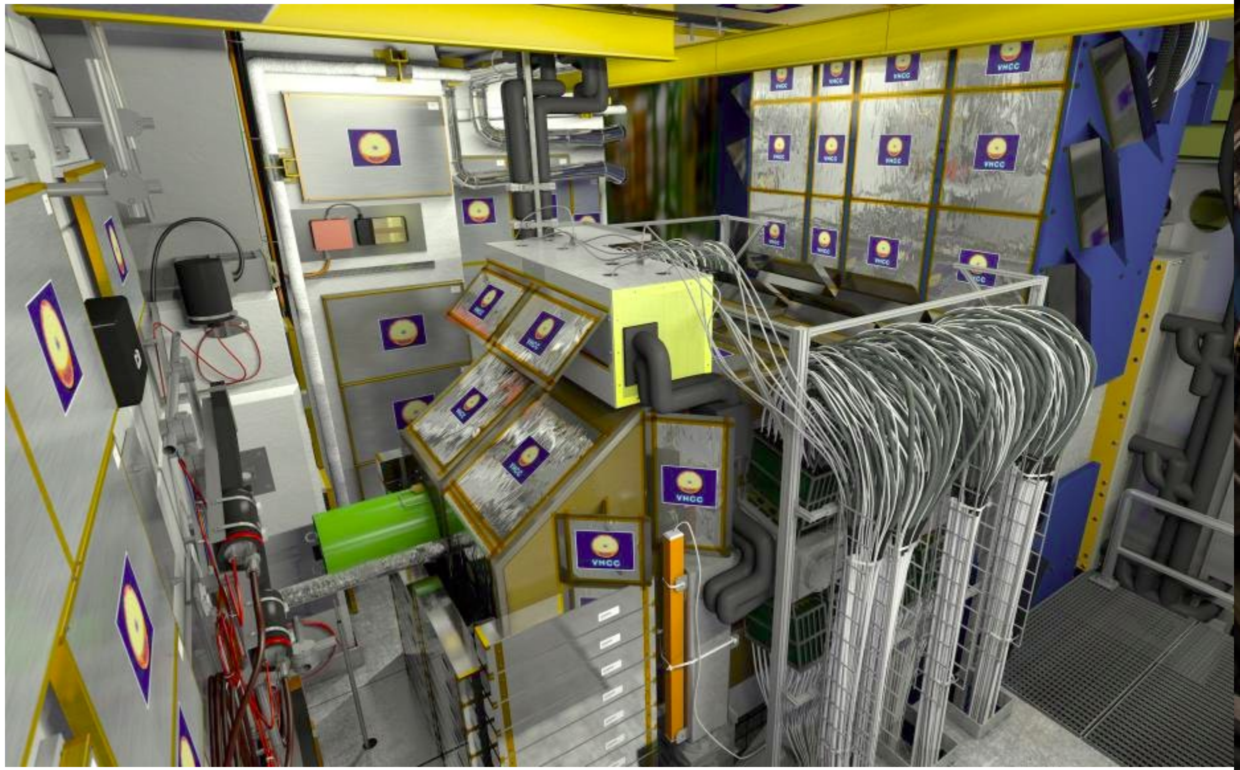
- The binding energies of magnetic monopoles in nuclei with large magnetic dipole moments estimated to be hundreds of keV *Nucl. Phys. B* ***255****, 465 (1985)*
- Close to 1 ton of Al MMTs deployed by MoEDAL
- After exposure, the MMTs are analyzed by a SQUID at ETH Zurich

Main sub-detector systems: NTDs

- Largest array (~120 m^2) of NTDs deployed at an accelerator
- Stacks of CR-39 (5 MIP threshold) and Makrofol (50 MIP threshold)
- Highly ionizing particle creates a latent track by displacing atoms, revealed by controlled etching
- Practically no Standard Model backgrounds



The MoEDAL detector



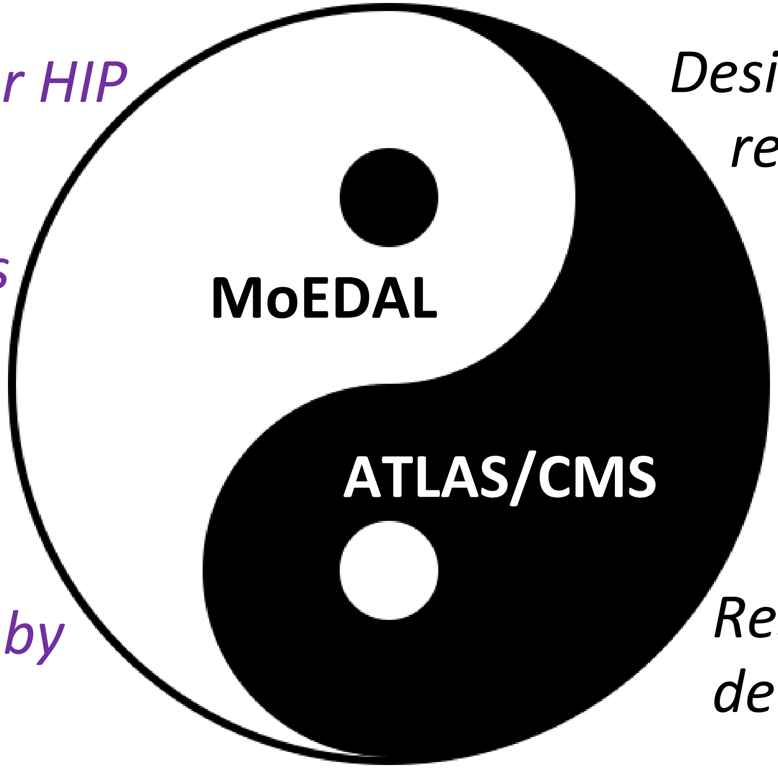
Complementarity

Designed & Optimized for HIP

Insensitive to SM backgrounds

Can directly detect & trap magnetic charge

Response calibrated by heavy ions



Designed & optimized for SM relativistic MIPs & photons

Sophisticated triggers

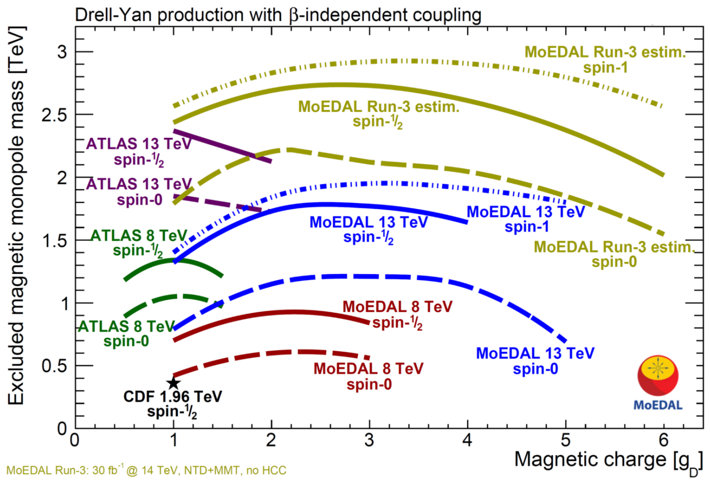
Can infer magnetic charge from tracking and dE/dx

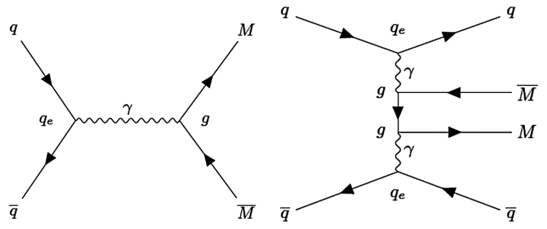
Response estimated from detailed Monte Carlo

Different systematics and mode of detection of MoEDAL compared to the ATLAS/CMS experiments → important validation of and insights into the potential joint observation

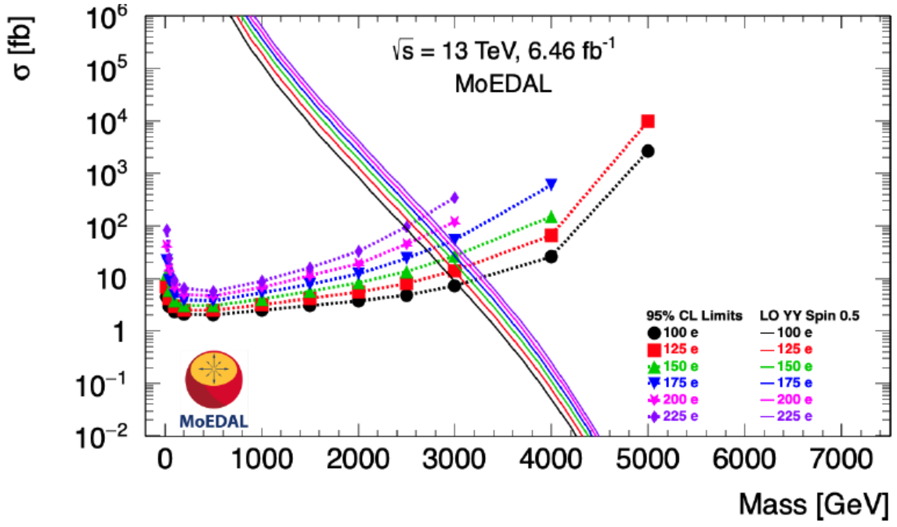
Some Earlier Results

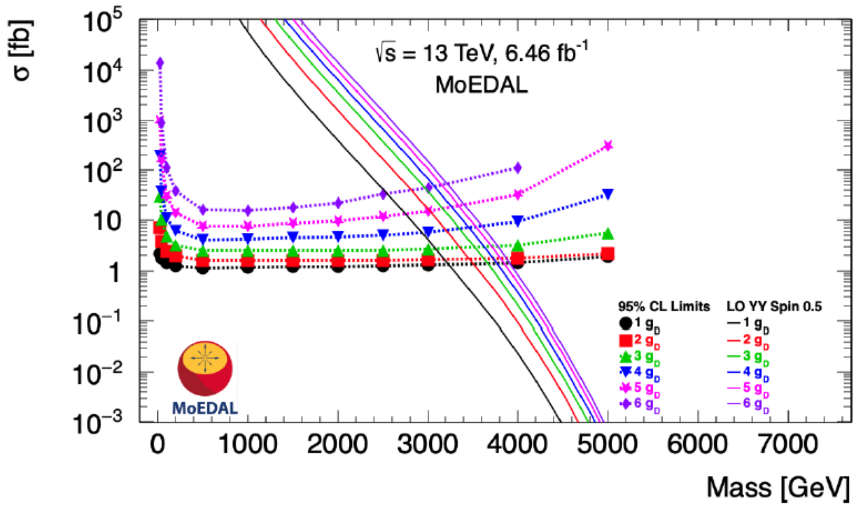
- "Magnetic monopole search with the full MoEDAL trapping detector in 13 TeV pp collisions interpreted in photon-fusion and Drell-Yan production". *Phys. Rev. Lett.* ***123***, *021802 (2019)*
- "First search for dyons with the full MoEDAL trapping detector in 13 TeV pp collisions". *Phys. Rev. Lett.* ***126***, *071801 (2021)*





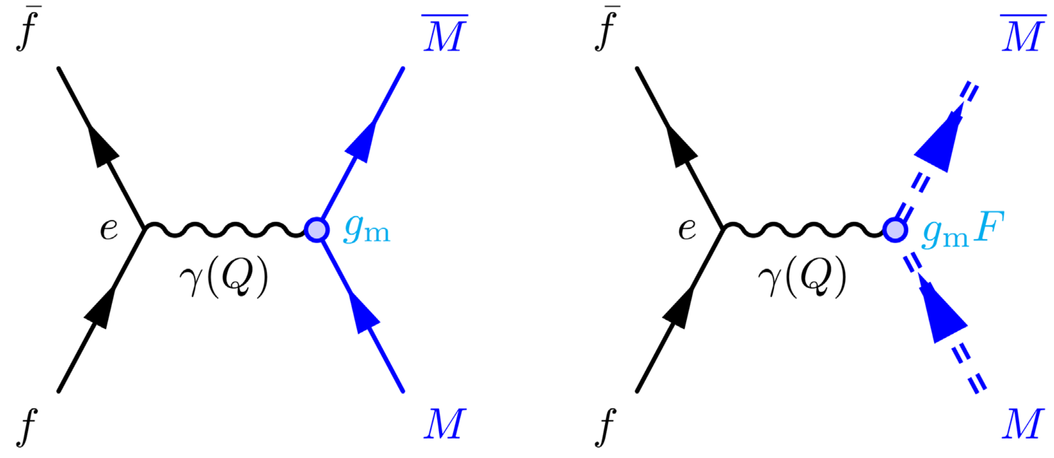
Recent Results





- "Search for Highly-Ionizing Particles in pp Collisions During LHC Run-2 Using the Full MoEDAL Detector"
  - arXiv:2311.06509
  - **Mass limits 0.79–3.9 TeV on monopoles with up to 10g_D magnetic charge and HECO with 5*e* – 350*e* electric charges**

Difficulties with collider searches for MMs



Int. J. Mod. Phys. A ***35****, No. 23, 2030012 (2020)*

1. Most recent models predict monopoles with internal structure – **composite monopoles**. But production of composite monopoles in elementary particle collisions is expected to be **suppressed** by a form factor, $e^{-4/\alpha} \sim 10^{-250}$. Consequently, all collider searches to date focused on point-like MM

2. Mass limits calculated with Feynman-like diagrams do not account for **non-perturbative nature** of large monopole-photon coupling. Any perturbatively-calculated cross section is indicative and can only be used to facilitate comparisons between experiments

The Schwinger mechanism

- Spontaneous creation of electron–positron pairs in presence of an extremely strong electric field
  - $E_s = \frac{m_c^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18}\, V/m$

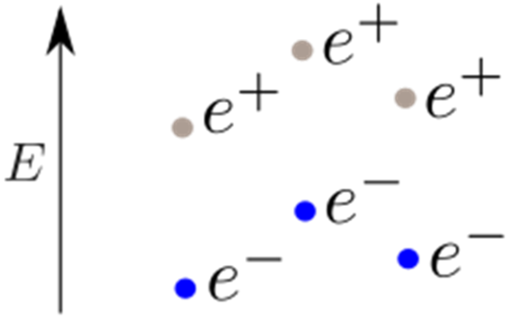
- Due to the inherent instability of QED vacuum in presence of a strong electric field
  - Pair production originates from the quantum mechanical decay of an electromagnetic field; vacuum pairs tunnel into existence

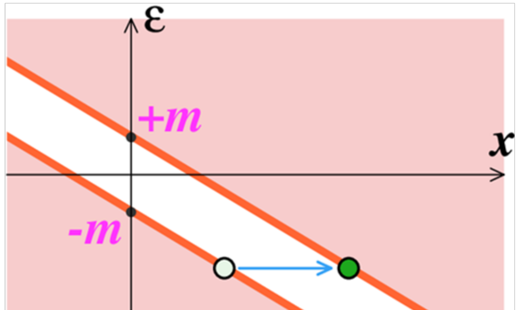
- Rate is calculable non–perturbatively using semi–classical instanton techniques

On Gauge Invariance and Vacuum Polarization

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
(Received December 22, 1950)

$$\Gamma = \frac{(eE)^2}{4\pi^3 c\hbar^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\frac{\pi m^2 c^3 n}{eE\hbar}}$$

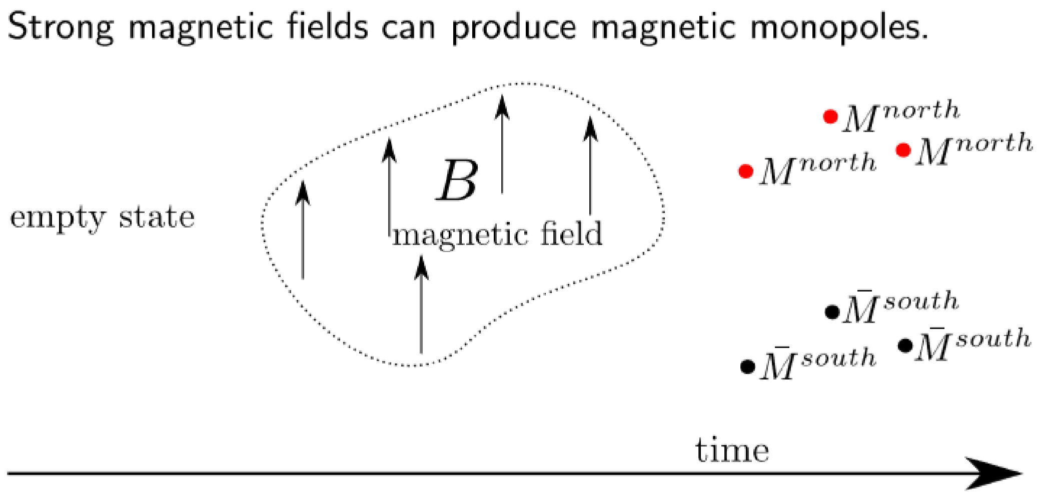




Prog, Part. Nucl. Phys. ***87****, 1 (2016)*

The Schwinger mechanism at the LHC

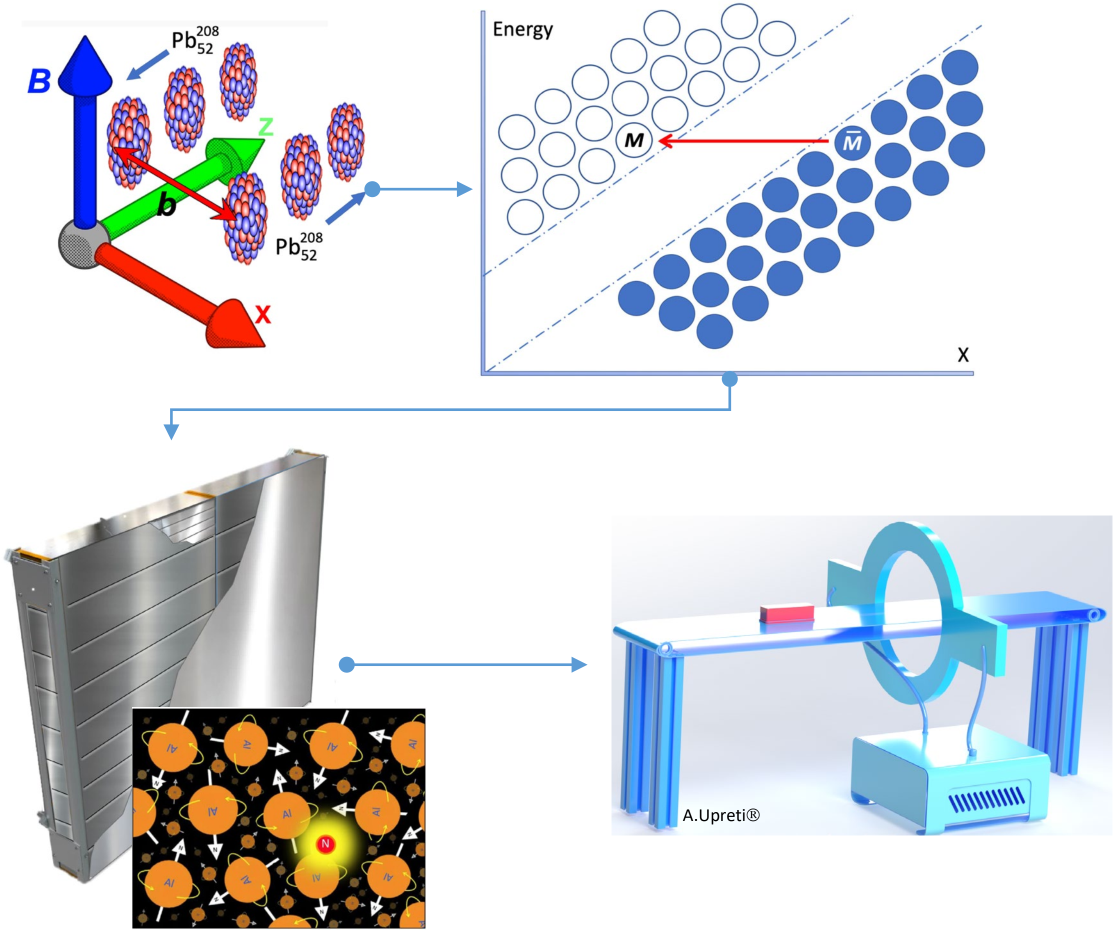
- By electromagnetic duality, a sufficiently strong magnetic field would produce magnetic monopoles via the same mechanism
- Ultraperipheral Pb-Pb collisions at the LHC have produced the strongest peak magnetic fields in the known universe
  - **B ~ 10^{16} T, as compared to ~ $10^{11\text{-}12}$ T on a magnetar's surface**
- **Apart from the nonperturbatively calculated cross section, no exponential suppression is expected due to the coherence of the field over the scale comparable to the monopole size**
  - In fact, the strong coupling and finite size only enhances the production of Schwinger monopoles!



Nucl. Phys. B 194, 38 – 64 (1982)

MoEDAL search for Schwinger monopoles

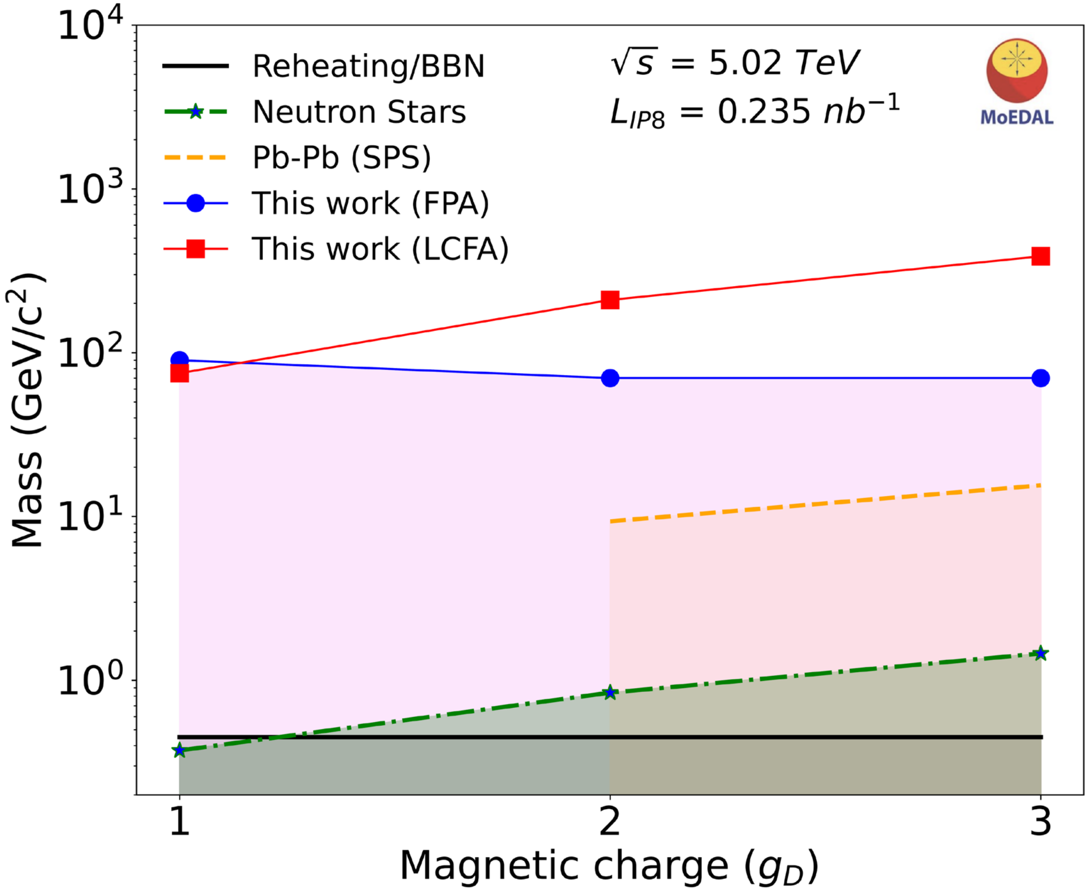
- The 2018 LHC heavy-ion run
  - Relativistic, bare Pb nuclei, γ = 2675
  - CM energy of 5.02 TeV per collision
  - Ultra-peripheral collisions with B_{peak} ~ 10^{20} G and ω ~ 10^{26} s^{-1} (inverse decay time)
- 880 kg of MoEDAL's MMTs exposed to integrated luminosity of 0.235 nb^{-1}
  - ~$2{\cdot}10^{9}$ Pb-Pb collisions in total
  - ~$6{\cdot}10^{8}$ ultraperipheral



Results of the search

- No statistically significant signal was observed
- The existence of a monopole with $g > 0.5g_D$ in the trapping volume was excluded at more than 3σ
- **1st search sensitive to composite monopoles**
- **1st reliable limits on monopole mass**
  - **Monopoles lighter than ~75 GeV and 1-3 g_D do not exist**

Nature 602 (2022) 7895, 63-67

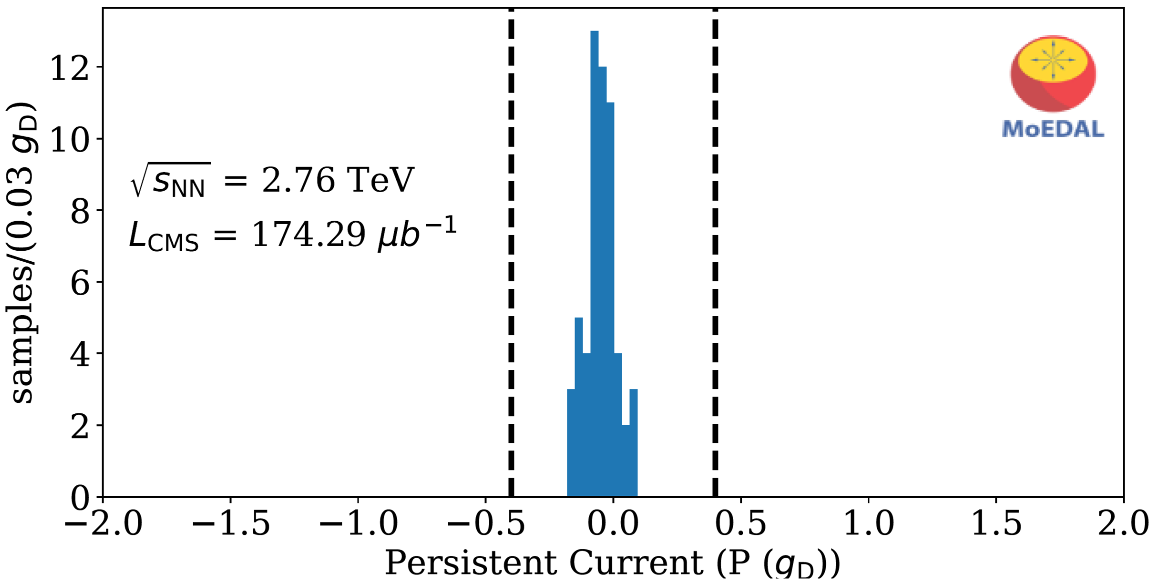


Most recent MoEDAL search

- Dirac's monopole has charge of 1 Dirac unit. In GUT and other BSM theories the fundamental magnetic charge is typically larger
- The value depends on the global properties of the gauge group: in an SU(N) theory, a minimal magnetic charge is typically of N Dirac units
    - In fact, finding the minimum charge would be a low-energy way to probe the structure of the gauge group!
- In string theories, monopoles are also integer multiples of Dirac charge
- Experimentally, searching for large magnetic charges is difficult due to very large ionization losses – monopoles range out before reaching active materials
- A way to overcome this is to search as close to the source as possible – beam pipe!

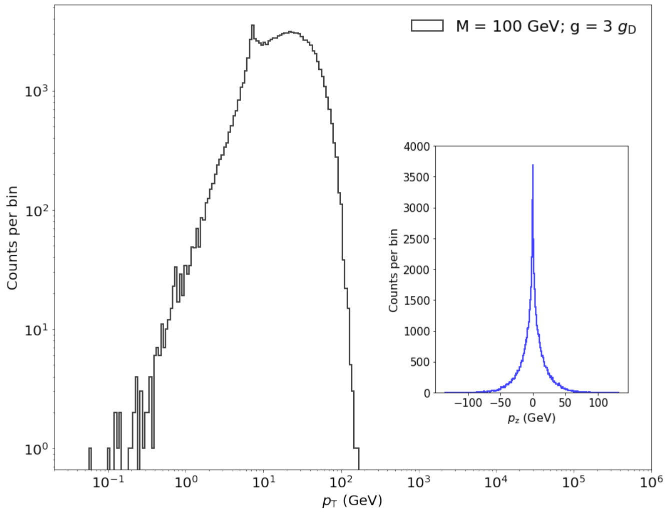
Most recent MoEDAL search

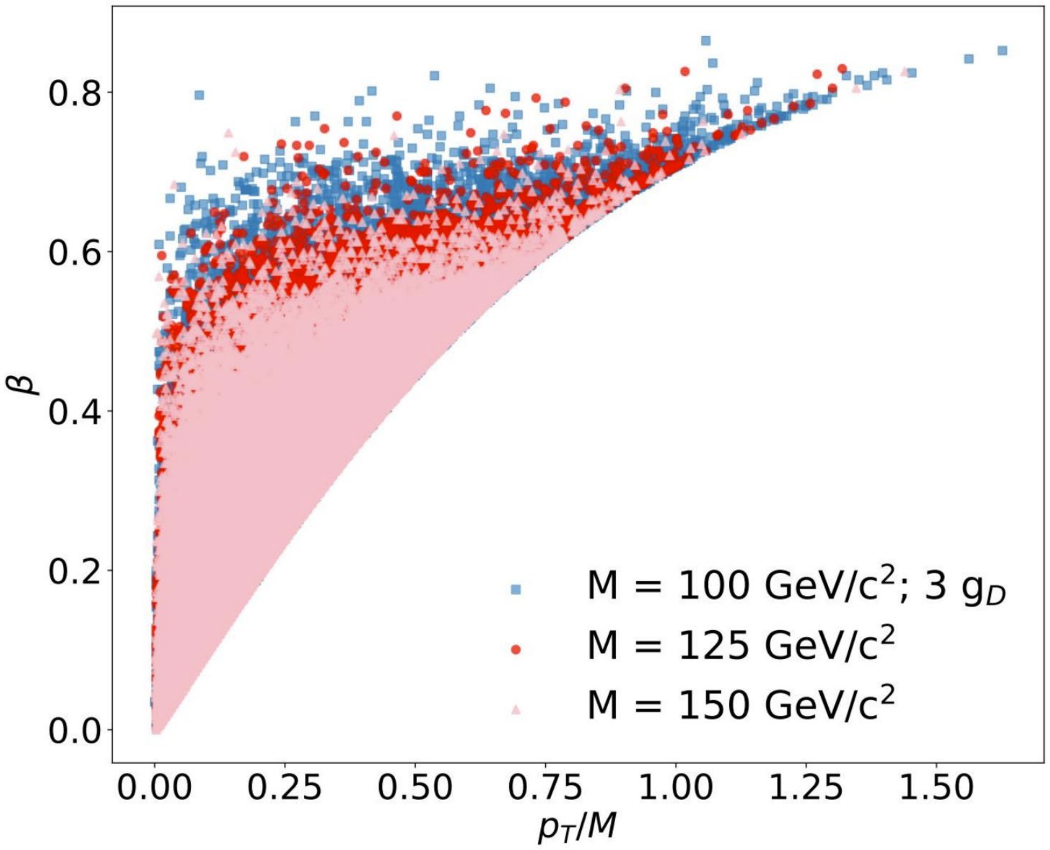
- Beryllium (nasty stuff!) pipe was sawed into pieces that were further crushed and scanned with a SQUID
- No persistent current observed in the beam pipe samples



Most recent MoEDAL search

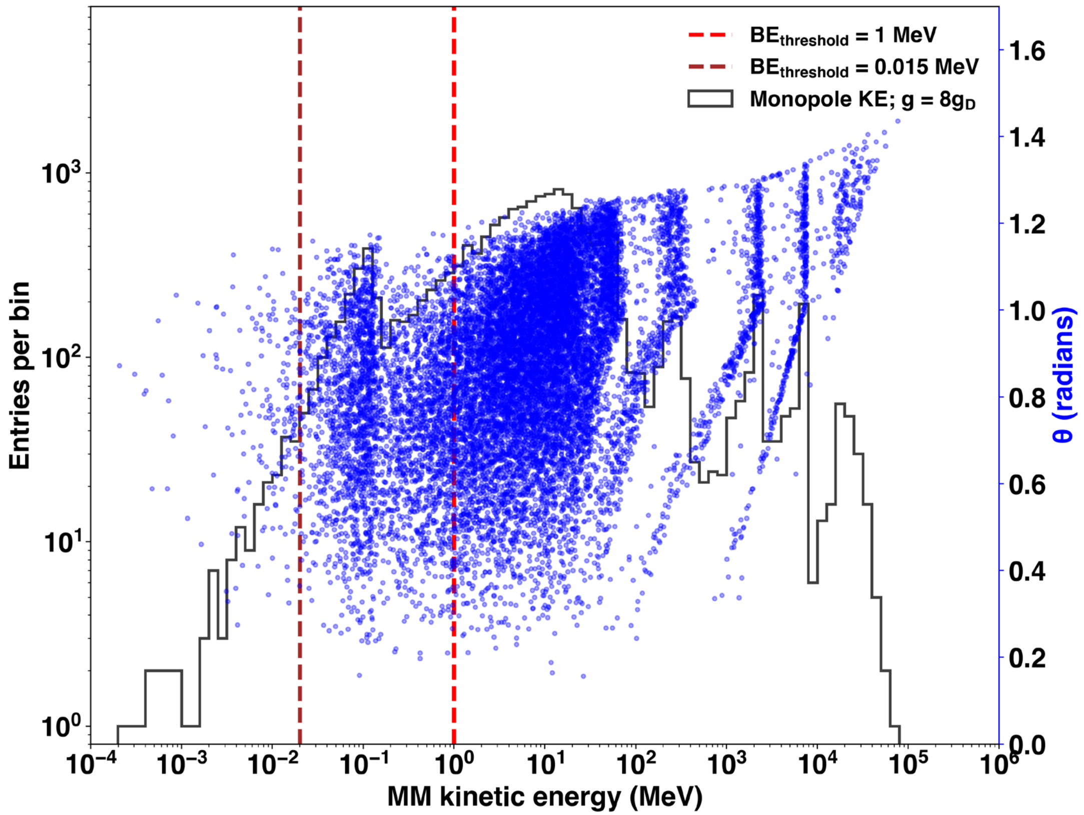
- Typical initial kinematics distributions given by theory and used in Monte Carlo simulations to calculate the MM trapping efficiency





Most recent MoEDAL search

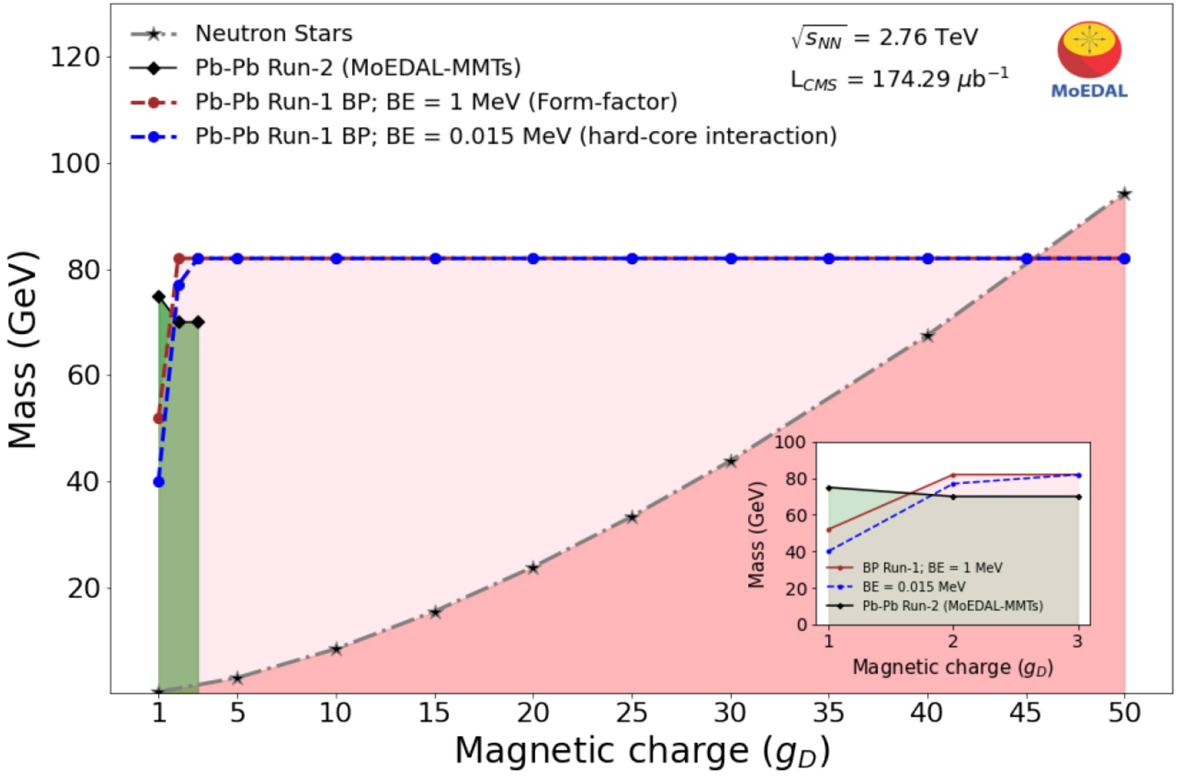
- Since there is a strong magnetic field at the CMS collision point, only those MMs/anti-MM that have initial direction against the field have a chance to turn around inside the beam pipe and at that point – having the minimal KE – get trapped forever



Most recent MoEDAL search

- The 1-mm thick, almost 2-m long Be pipe was exposed to 174 μb^{-1} of Pb-Pb collisions (2.76 TeV CM energy per nucleon pair) at CMS during Run-1
- The beam pipe was donated to MoEDAL, crashed, and searched with a SQUID magnetometer for the presence of trapped magnetic charge
- No signal was found, setting the first reliable mass limits on monopoles with world-leading sensitivity to large magnetic charges

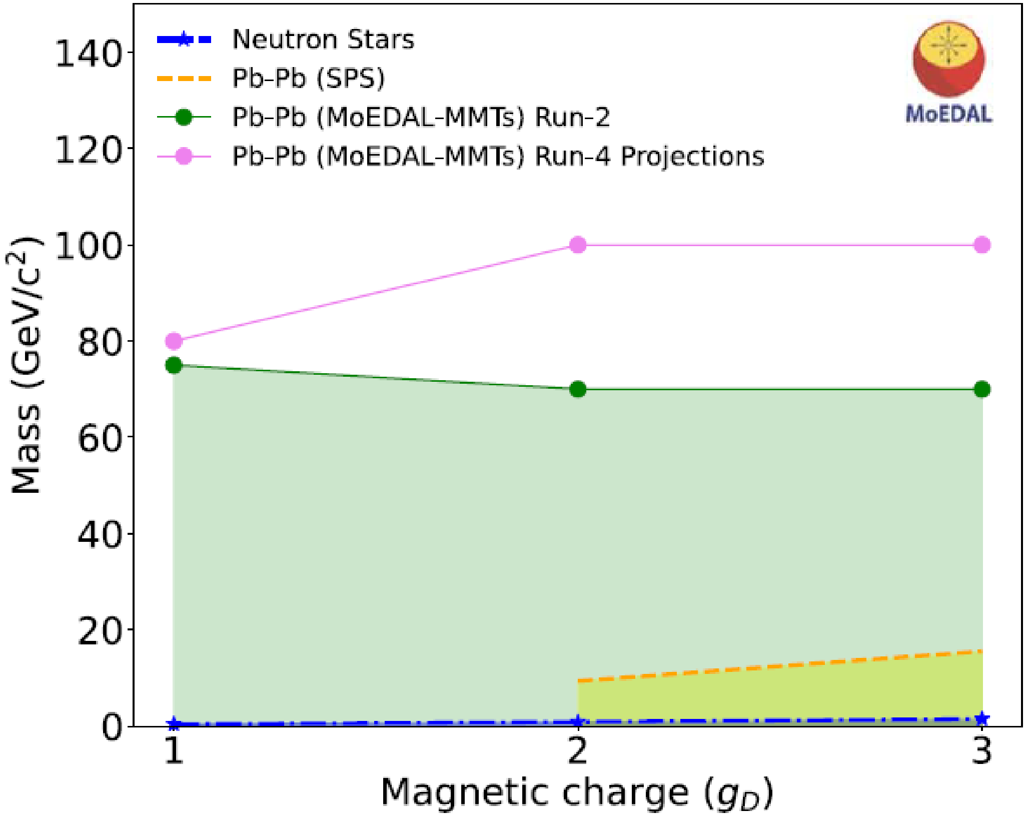
arXiv:2402.15682



Where to go from there?

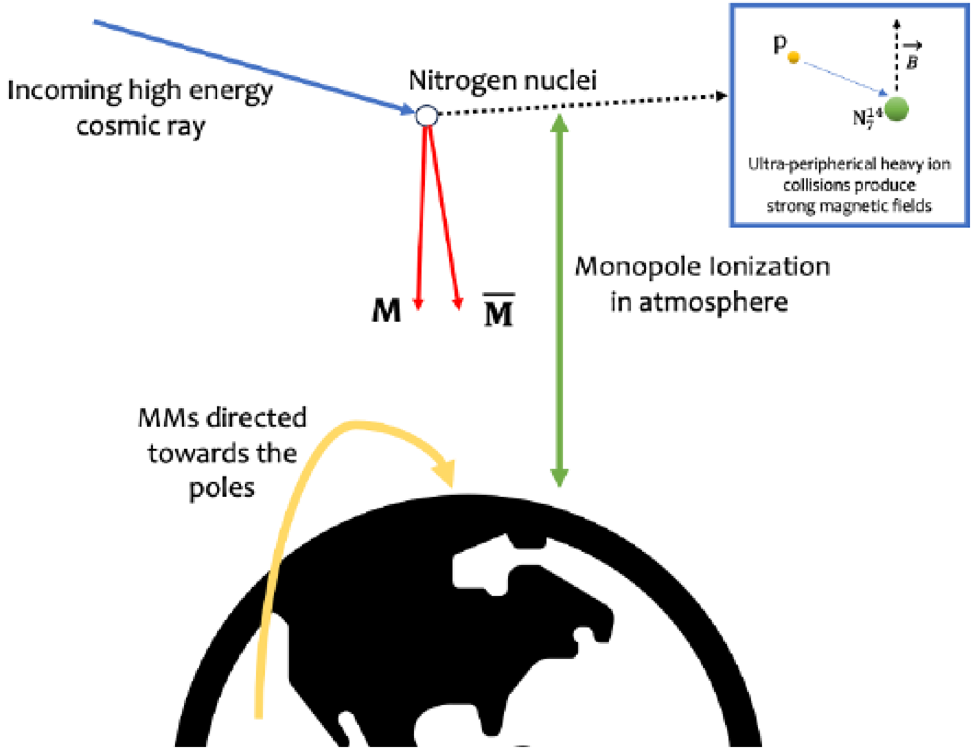
J. Phys. G, 50(5):050501, 2023

- The Schwinger mechanism opens a golden channel for magnetic monopole searches
- The current results are pioneering but not strong enough to reach the most interesting parameter space and test most of the existing models
- A. Upreti ran sensitivity projections for SNOWMASS for future LHC upgrades (HL-,HE-), and the LHC is unlikely to reach above 200-300 GeV/c^2



Where to go from there?

- The future hh collider, like SPPC, is the most reliable way to detect MMs or exclude the relevant models
  - The projections, which we hope to publish soon, show that 10^0 TeV/c^2 masses will be achievable
- But can anything else be done in the meantime, in the following 20 years or so?
- Working on several scenarios that could define the MM searches in the next decades
  - Slower MMs would slow down and be guided by the Earth's field towards the poles. Scanning the polar ice may allow achieving exposures of ~10^4 yr and more
  - Faster MM could be trapped in the iron or aluminum ore deposits with exposures of ~Myr! Commercial mines process Mtons of ore per year
  - Detectors like proposed by SCEP or simple NTDs could work in conjunction with cosmic ray observatories like Auger, TAO, or LHAASO to confirm or refute the suggestion that EHECRs, like the recent Amaterasu particle is a MM
- More on these in our upcoming publication!

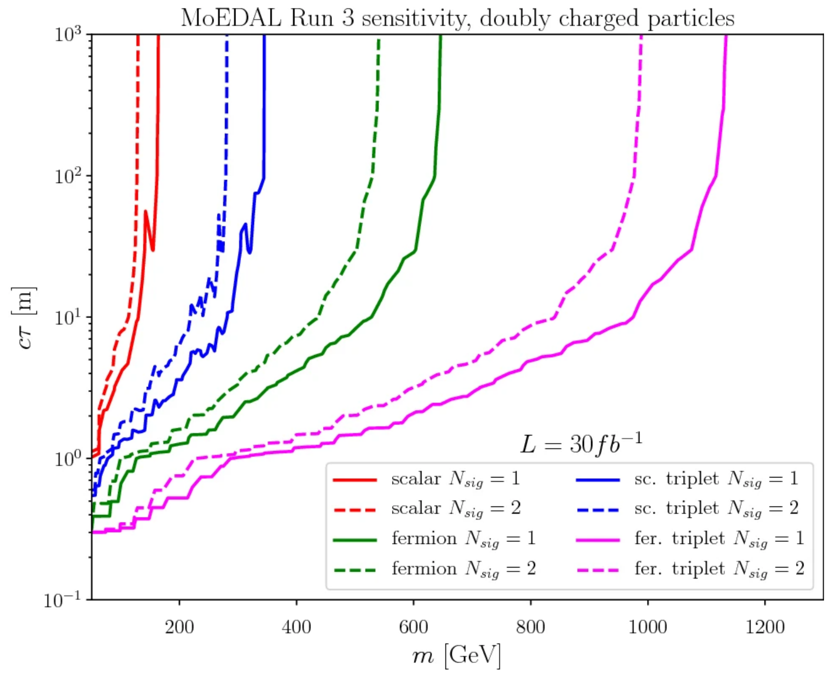


Summary

- The existence of magnetic monopoles is well motivated, but their mass and production mechanism are uncertain
- MoEDAL is a dedicated search for magnetic monopoles and other exotic particles at the LHC that established world-leading limits on production of monopoles and dyons in p-p collisions
- Enabled by recent theoretical advances, MoEDAL performed the first search for magnetic monopoles produced in Pb-Pb collisions via the Schwinger mechanism
    - First limit on MM masses based on nonperturbative cross section
    - Applies to composite monopoles
- MoEDAL will continue taking data in Run-3, extending its reach to monopoles with larger mass and magnetic charge, as well as expanding the search to other long-lived and milli-charged particles
- Looking further ahead, we have ideas on how to finally catch this elusive particle in cosmic ray or with the next collider

Searches for other Exotics with MoEDAL

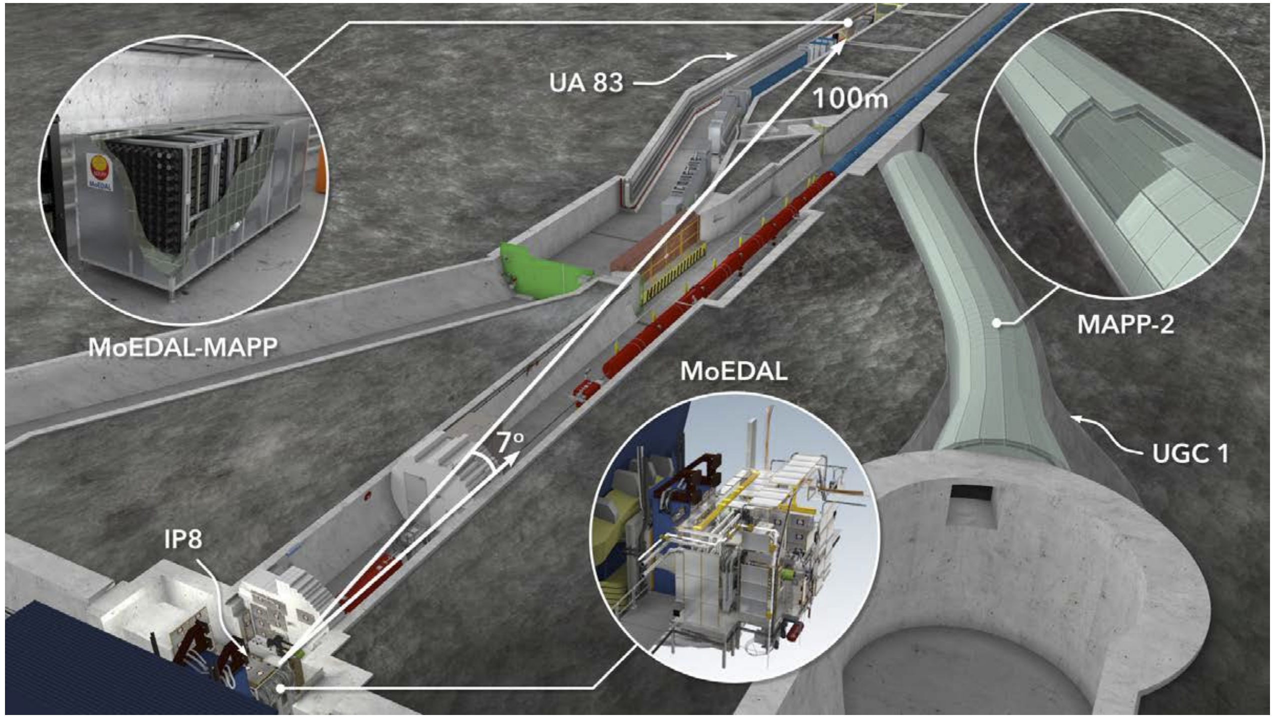
- MoEDAL NTDs are also sensitive to highly electrically charged objects (HECOs) that may include aggregates of quark matter, Q-balls, or micro black hole remnants
  - First paper on Run-1 dataset has been published in EPJC in 2022
- If sufficiently slow-moving, even singly or multiply ($\lesssim 10$) charged particles will leave a track in the NTDs
  - Supersymmetry offers such long-lived states: sleptons, R-hadrons, charginos
  - Multiply charged scalars or fermions are, for example, predicted in several neutrino mass models.



*EPJC **80**, 572 (2020)*

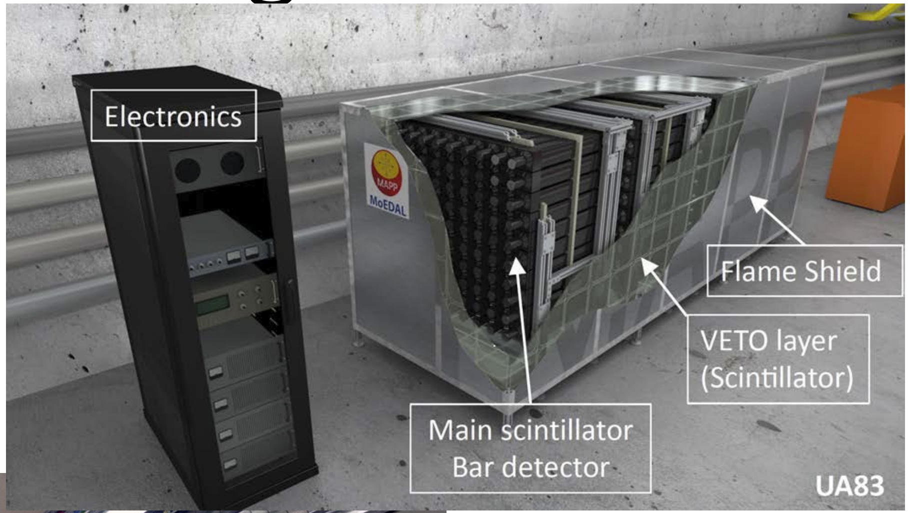
MoEDAL Apparatus for Penetrating Particles

- Approved by the CERN Research board end of 2021
- Extension of MoEDAL that will provide competitive sensitivity to milli-charged particles (mCPs) with electric charges down to 0.001 e
- Placed in UA83, ca. 100 m from the IP8



MoEDAL Apparatus for Penetrating Particles

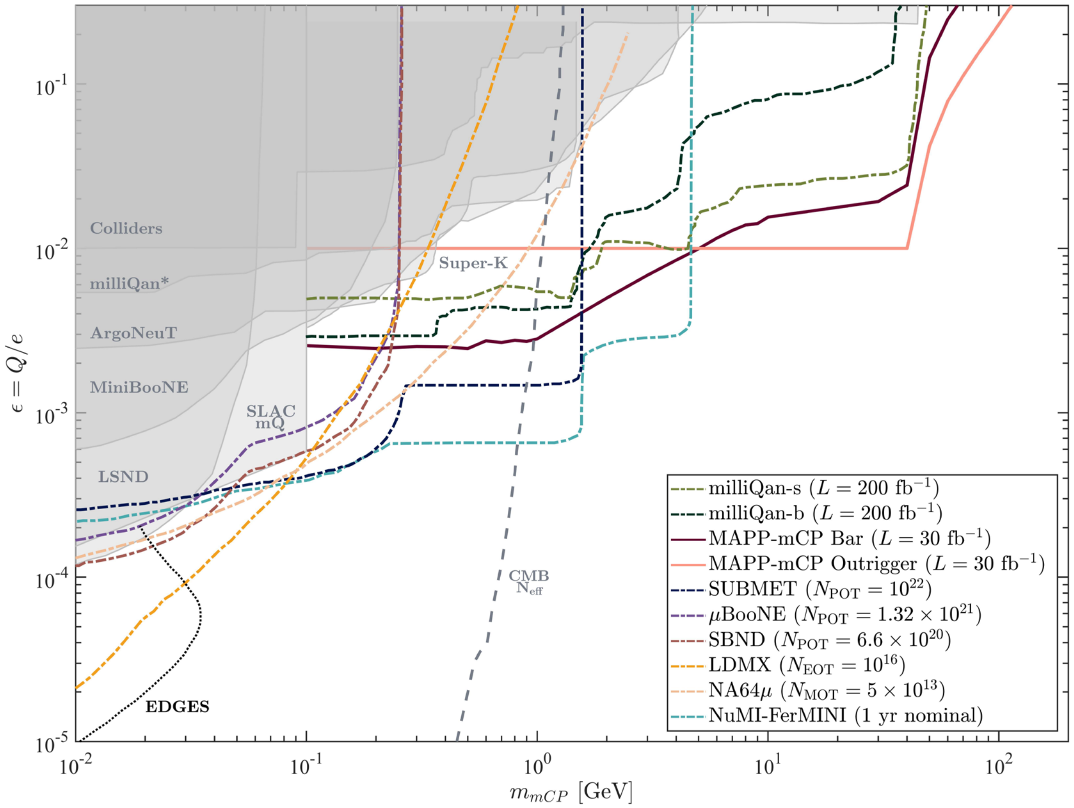
- Detector consists of 4 sections with 10×10 array of 100 scintillator bars each
  - Protected by a hermetic VETO counter system
  - Each through-going particle sees 3 m of scintillator readout by a coincidence of 4 low noise PMTs
  - Being installed in UA83, ~100 m from the IP8



UA graduate student Aditya Upreti installing the MAPP's scintillators into the support structure, CERN, February 2022. (Image: CERN News)

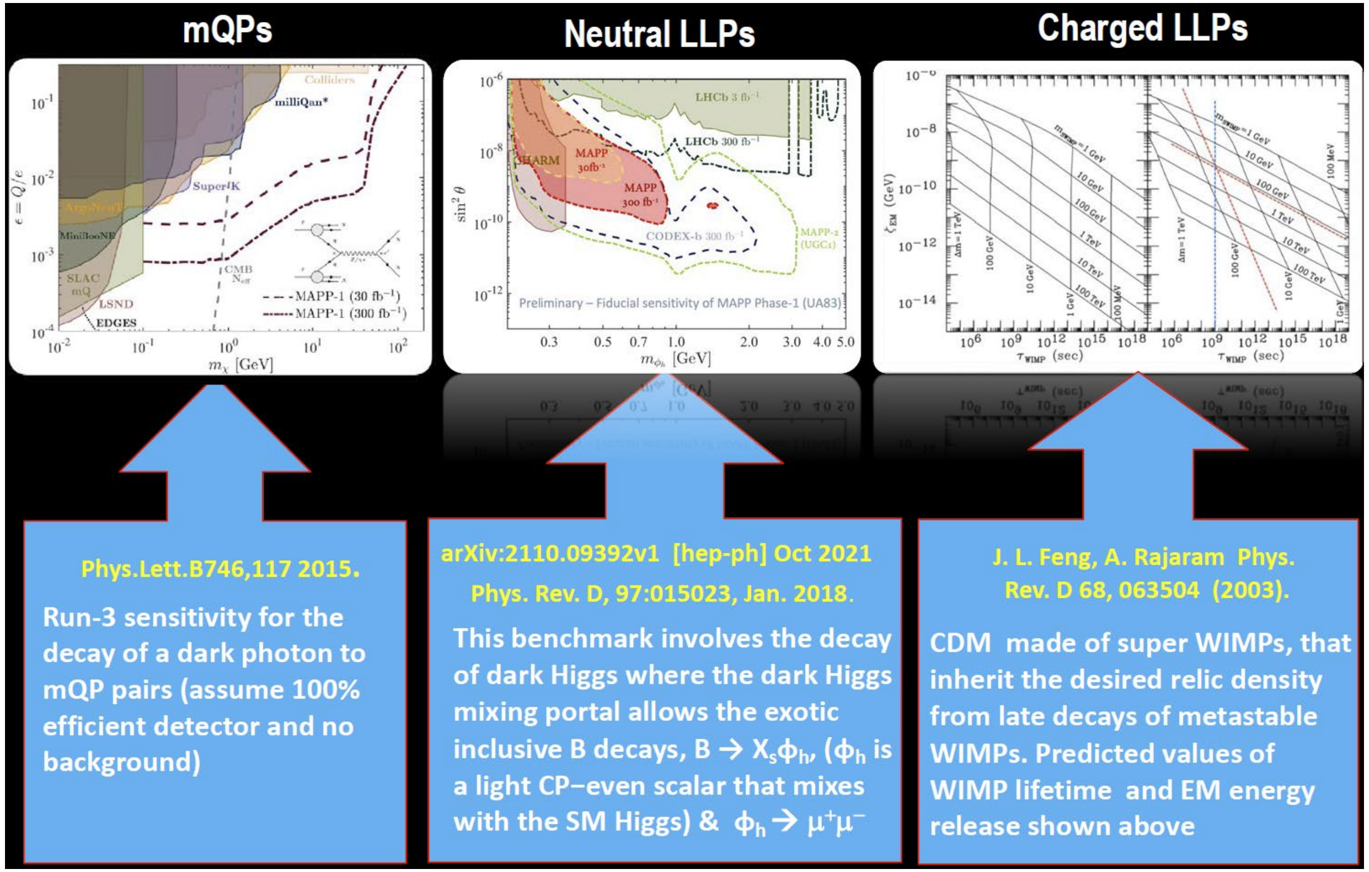
MoEDAL Apparatus for Penetrating Particles

- MAPP will be sensitive to mCPs, which are predicted within the framework of (massless) vector portal dark sector models
- mCPs' ionization losses are too low to be effectively studied by ATLAS and CMS
- In Run-3, MAPP will be competitive/complementary with/to milliQan
    - while covering different pseudo-rapidity range and having different systematics
- See also talk by Giovanna Cottin



Existing bounds and projected sensitivity for mQPs, for models with a massless dark photon

MAPP physics program



Recent Theoretical Advances in low-mass Monopole Solutions

Relative low-scale GUT-LIKE MONOPOLES (~ 10^3 – 10^9 GeV)
from appropriate symmetry breaking patterns of special BSM Gauge Groups
e.g. D-brane inspired trinification $SU_C(3) \times SU_L(2) \times SU_R(2)$

Detectable @ LHC (Directly or indirectly)
or cosmically, with magnetic charges ≥ $2g_D$

T. W. Kephart, G.K. Leontaris, Q. Shafi
JHEP 1710 (2017) 176

Electroweak Monopoles in extensions of the Standard Model
with non-minimal Higgs coupling in hypercharge sector
with masses m ~ 4-6 TeV

Y.M. Cho, K. Kim, J.H. Yoon
Eur.Phys.J. C75 (2015) no.2, 67

Ellis, NEM, You, PLB 756, 25 (2016)

String-Inspired Born-Infeld (BI)Hypercharge sector SM extension
From light-by-light searches in LHC → **monopole mass ≥ 11 – 14 TeV**
To play a role in (delay) electroweak phase transition in Universe and
be consistent with BBN mass of monopole ~ 9.3 x 10^3 – 2.3 10^4 TeV

S. Arunasalam, A.Kobakhidze
Eur.Phys.J. C77 (2017) no.7, 444 &
arXiv:1810.10696;
NEM, Sarben Sarkar. ***Universe* 5**
(2018) 1, 8 [arXiv1812.00495]
Ellis, NEM, You, PRL118(2017),261802

String-Inspired magnetic monopoles from global monopoles
in the presence of antisymmetric tensor torsion-like axion fields
Torsion (axion) charge magnetic charge. Mass is free parameter

NEM, Sarben Sarkar.
Phys.Rev. D97 (2018) no.12, 125010
&

Electroweak scale monopoles (890 GeV-3 TeV),in models with
non-sterile right-handed neutrinos + complex Higgs triplets + doublets
+ real Higgs triplet (Custodial symmetry) → model also predicts neutrino
masses → quantisation prediction for weak mixing angle

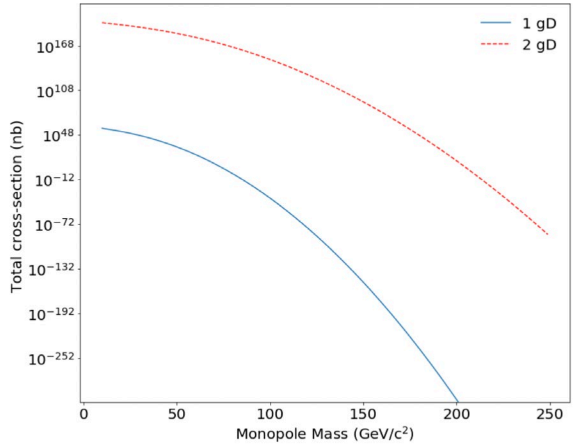
P.Q. Hung, arXiv:2003.02794
***(Nucl.Phys.B* 962 (2021) 115278)**

Hung, Ellis, NEM, arXiv: 2008.00464

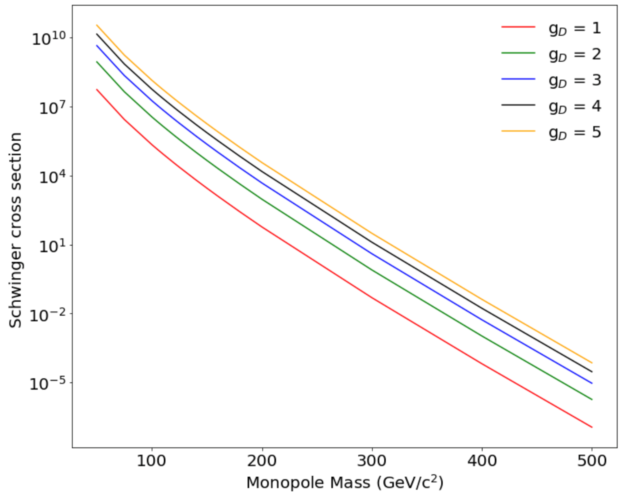
Two cross section approximations

- Two complementary calculations with uncorrelated uncertainties
- **Free-particle approximation (FPA)**
  - The spacetime dependence of the electromagnetic field of the heavy ions is treated exactly, but monopole self-interactions are neglected
  - *Phys. Rev. D **104**, 015033 (2021)*
- **Locally-constant field approximation (LCFA)**
  - The spacetime dependence of the field is neglected but self-interactions are treated exactly
  - *Phys. Rev. D **100**, 015041 (2019)*
- **While neither is complete, both are expected to yield conservative lower limits**
  - For FPA, the leading effects of self-interactions have been shown to enhance the cross section
  - Same for the LCFA and the leading effects of spacetime dependence

LCFA

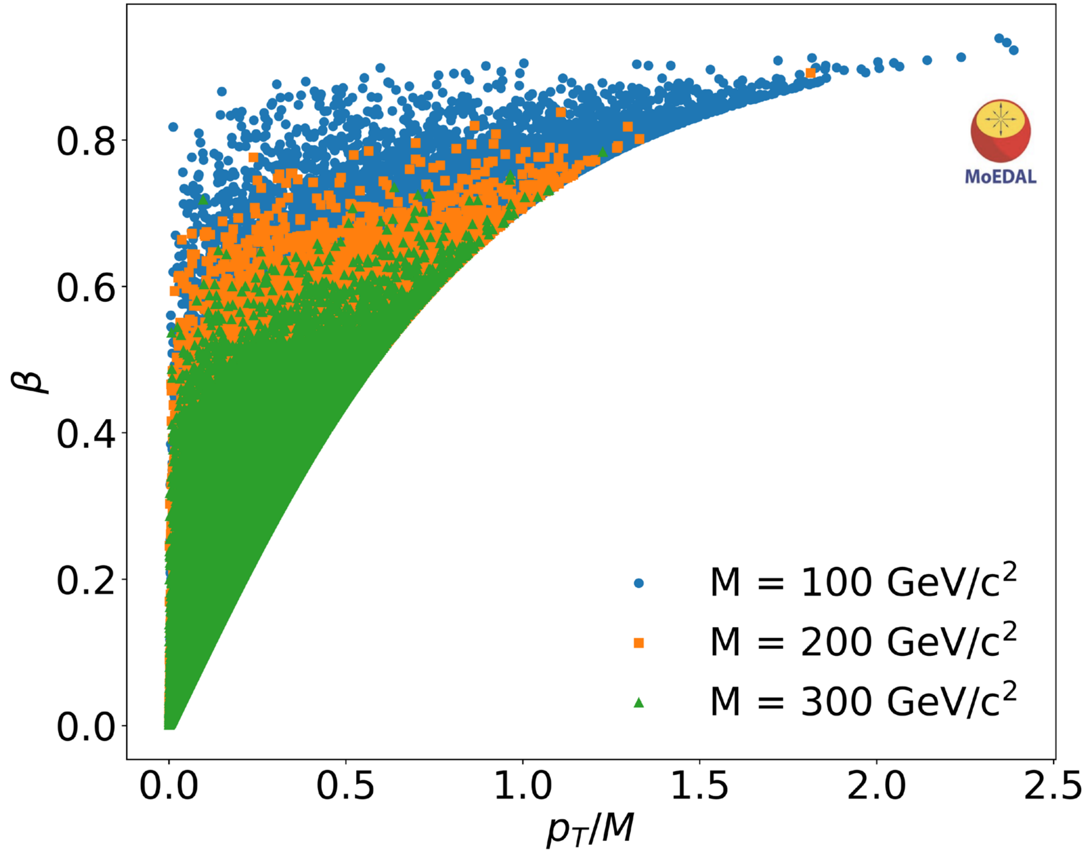


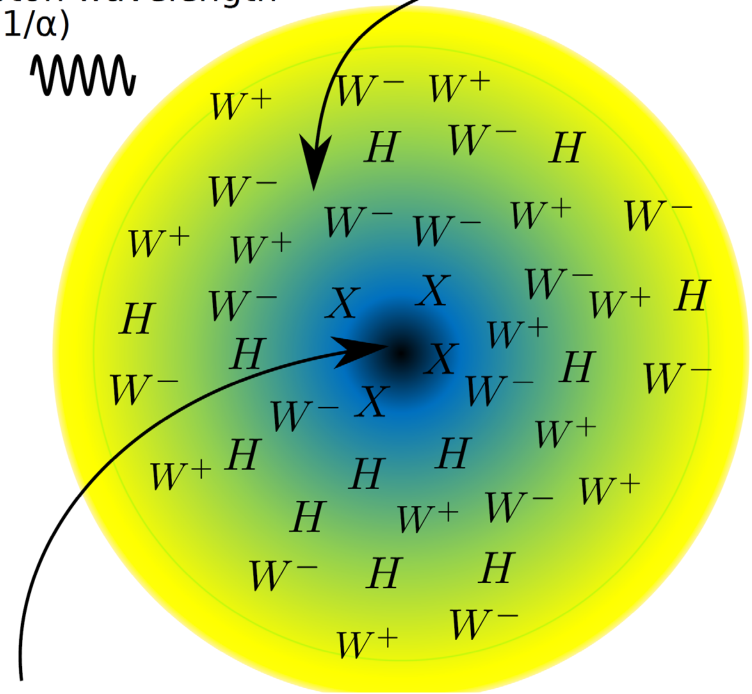
FPA



Kinematics

- Based on the FPA approach because at the LHC energies the momentum distribution is mainly due to the time dependence of the electromagnetic field
  - *Phys. Rev. D **104**, 015033 (2021)*

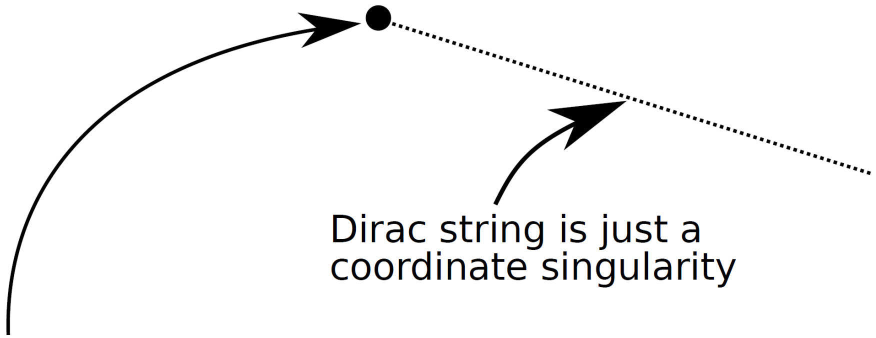




Composite

Consistent QFT of elementary monopoles exists

Any mass is possible



Point-like