# Searching for Magnetic Monopoles and other Exotics with MoEDAL

*Igor Ostrovskiy (University of Alabama)*

*on behalf of the MoEDAL collaboration*

# Outline

- Magnetic Monopoles
- MoEDAL
  - Detector
  - Complementarity with ATLAS
- Recent results
- MAPP – MoEDAL Apparatus for Penetrating Particles
- Outlook

# 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 **can contain magnetic monopoles**

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

- Mass is unknown. While the GUT scale monopole (~$10^{16}$ GeV) received the most interest earlier, several recent models point to possibility of monopoles with masses **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)*

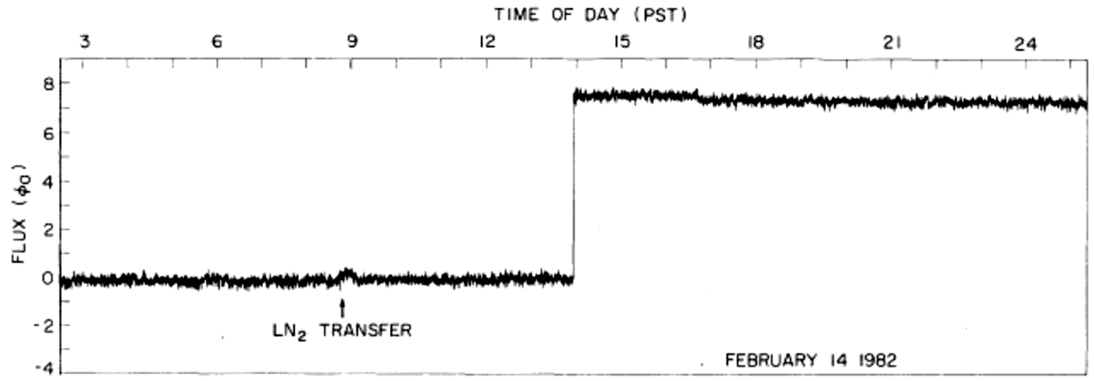
# Magnetic Monopole's basic properties

| | |
|---|---|
| $e \cdot g_D = \frac{\hbar c}{2} n \rightarrow g_D = \frac{n}{2\alpha} e \Rightarrow$ <br> $\mathbf{1 g_D = 68.5 \cdot e}$ | • Depending on the model, the fundamental charge could be $g_M = 2 \text{ or } 3 g_D$ (see talk by Q. Shafi) |
| $\frac{\boldsymbol{g_D^2}}{\boldsymbol{\hbar c}} \sim \mathbf{34}$ | • 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** |
| $\boldsymbol{-\frac{dE}{dx} \sim \frac{Z}{A} g_M^2 \cdot [\ln(\beta^2 \gamma^2) + \ldots]}$ | • Fast monopoles are highly ionizing! $\frac{dE}{dx} \sim g_M^2$= **4700 MIP** for $1 g_D$ <br> • Ionization of $g_M$ **increases with β**, as opposite to $e$ |

# Magnetic monopole searches

The Cabrera's event, 1982

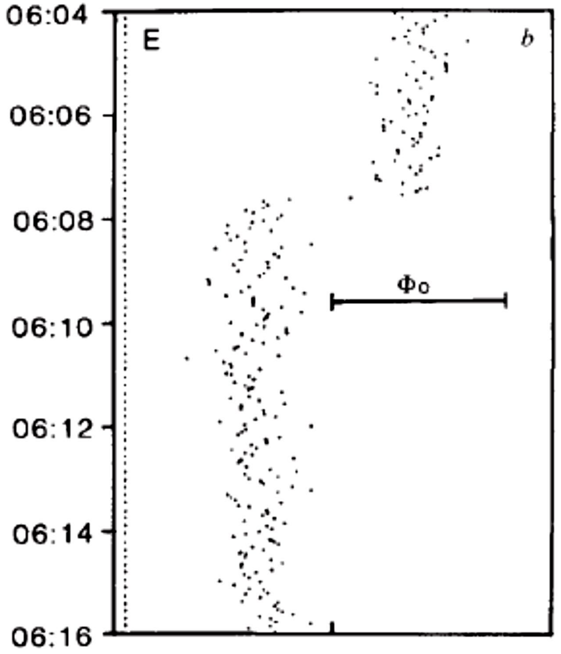
**20 cm²**, induction (SQUID)




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

Imperial College event, 1985

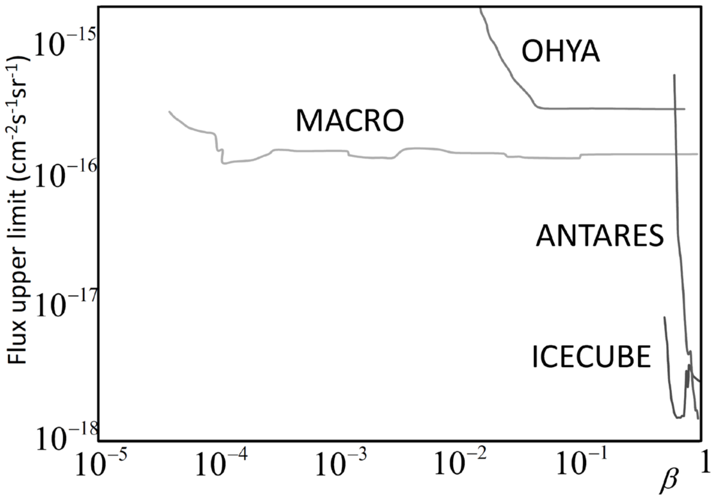
**0.18 m²**, induction (SQUID)



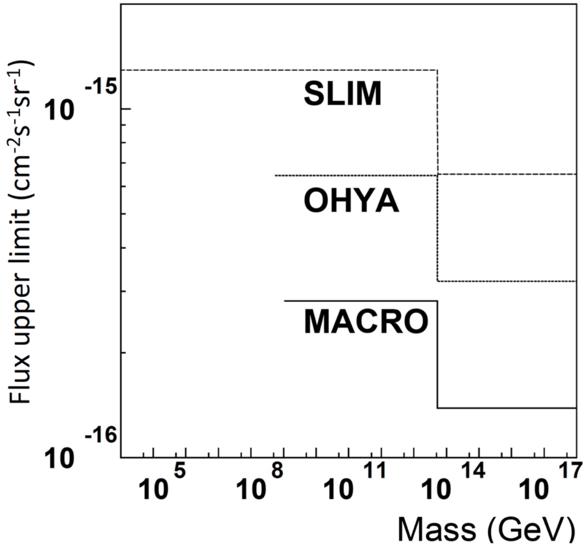

*Nature* ***321****, 402 - 406 (1986)*

# 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

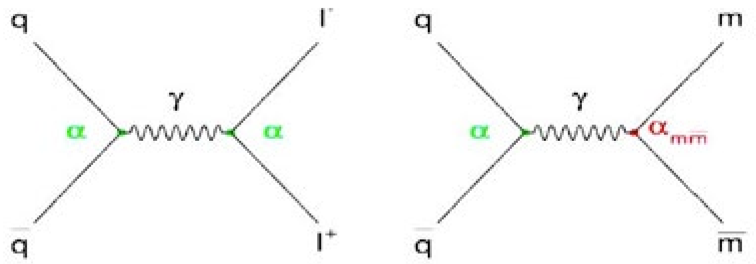



*Particle Data Group review (2021)*

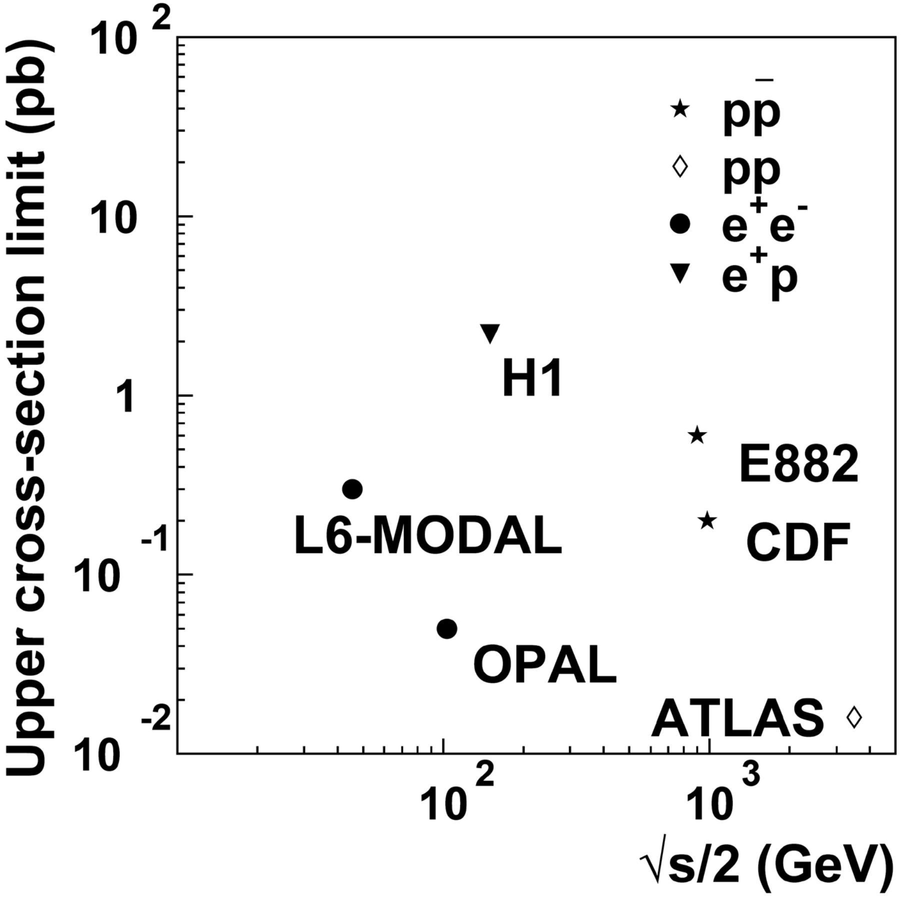


# Magnetic monopole searches

- 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

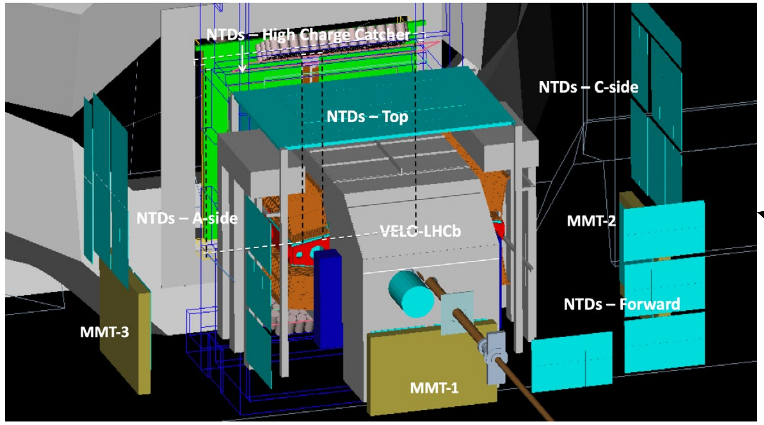


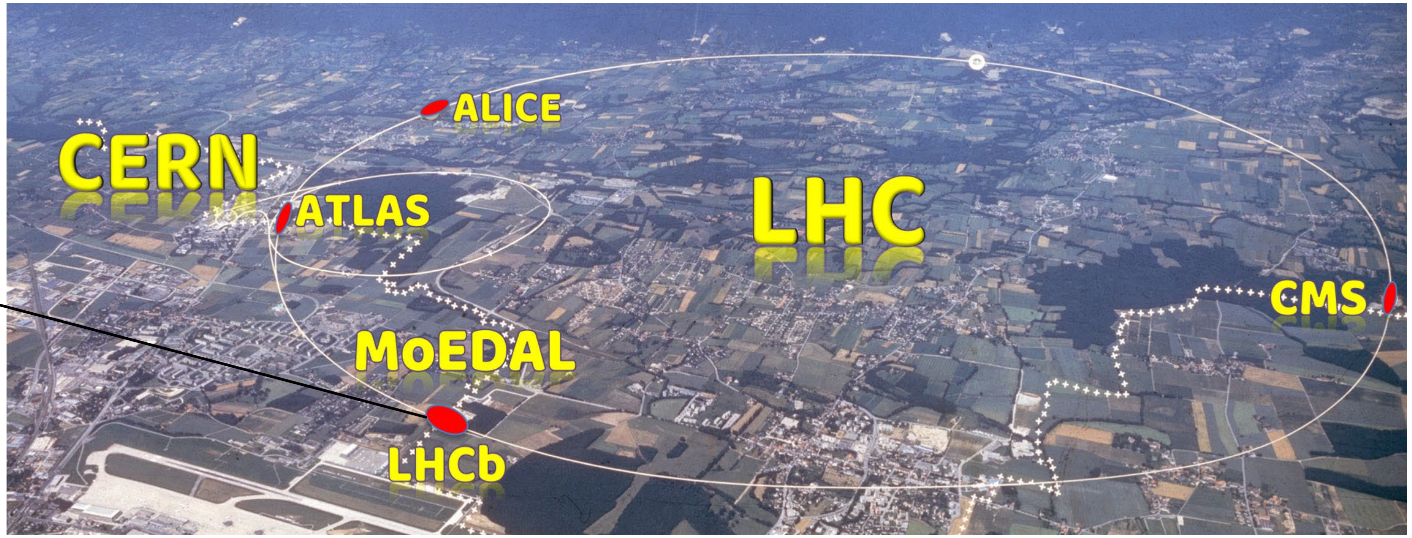

Drell-Yan production




*Particle Data Group review (2016)*

# MoEDAL – dedicated search at the LHC

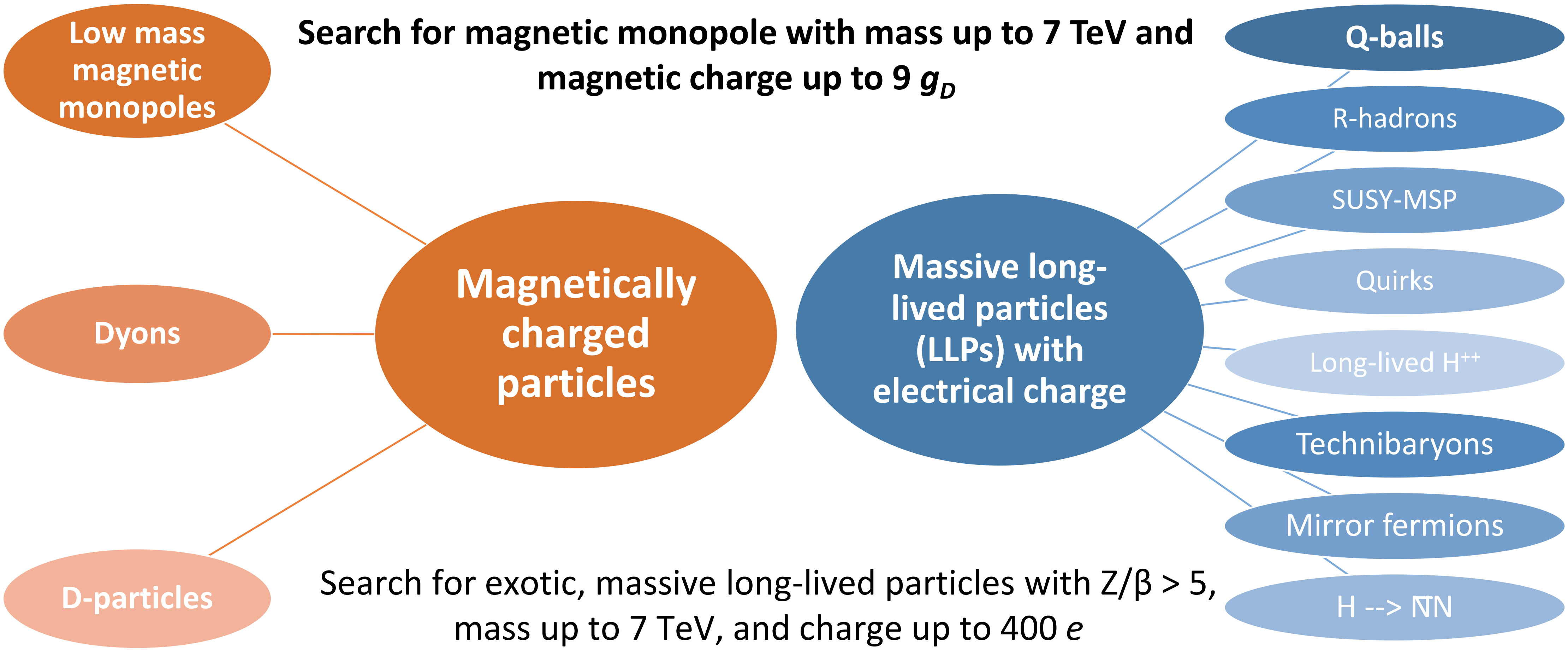



- “Monopole and other Exotics Detector At LHC” optimized to search fo **magnetic monopoles** and other highly ionizing particles with magnetic and/or electric charge (dyons, nuclearites, Q-balls, )
- ~70 physicists from >20 institutions from 7 countries. Approved by CERN 2009, started data-taking Spring 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

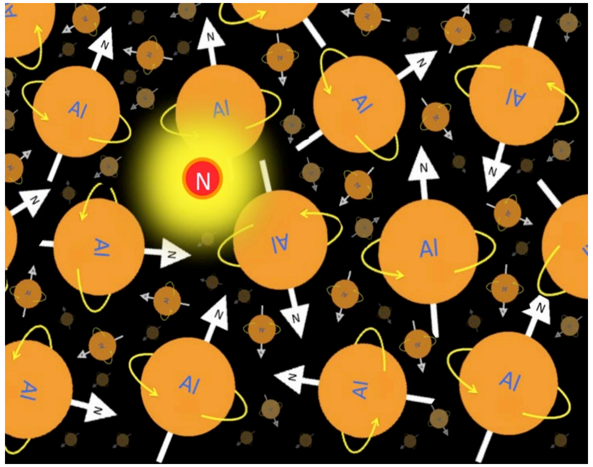
**Search for magnetic monopole with mass up to 7 TeV and magnetic charge up to 9 $g_D$**

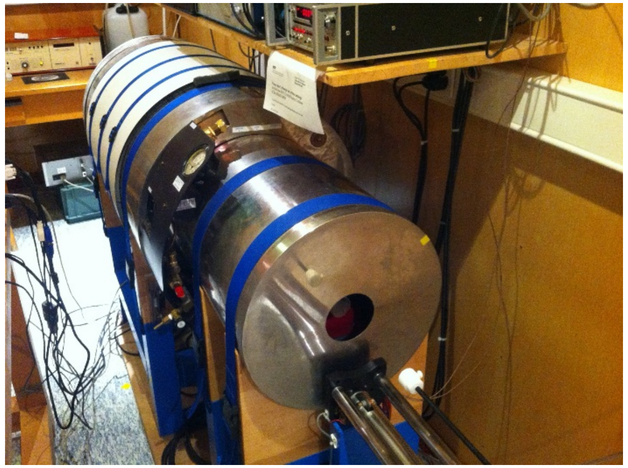



Search for exotic, massive long-lived particles with $Z/\beta > 5$, mass up to 7 TeV, and charge up to 400 *e*

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

# Main sub-detector systems: MMTs

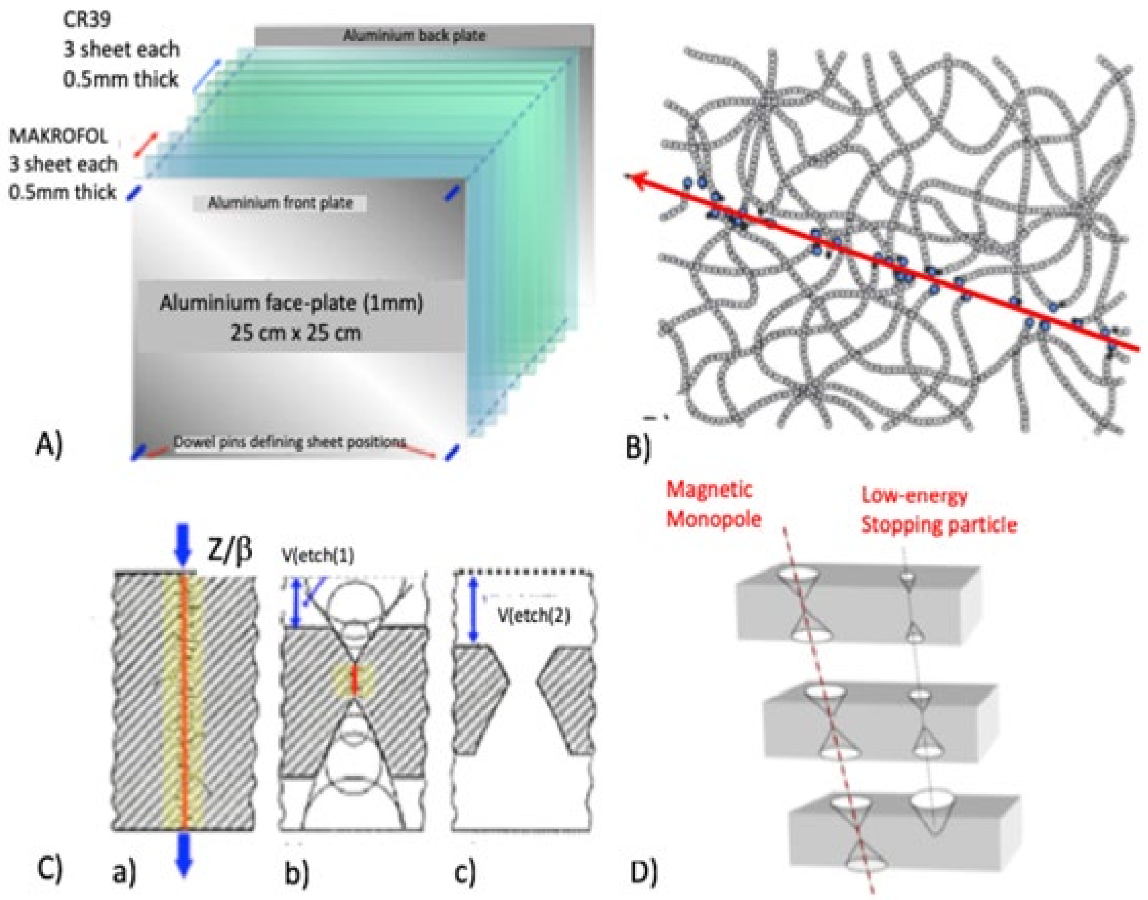


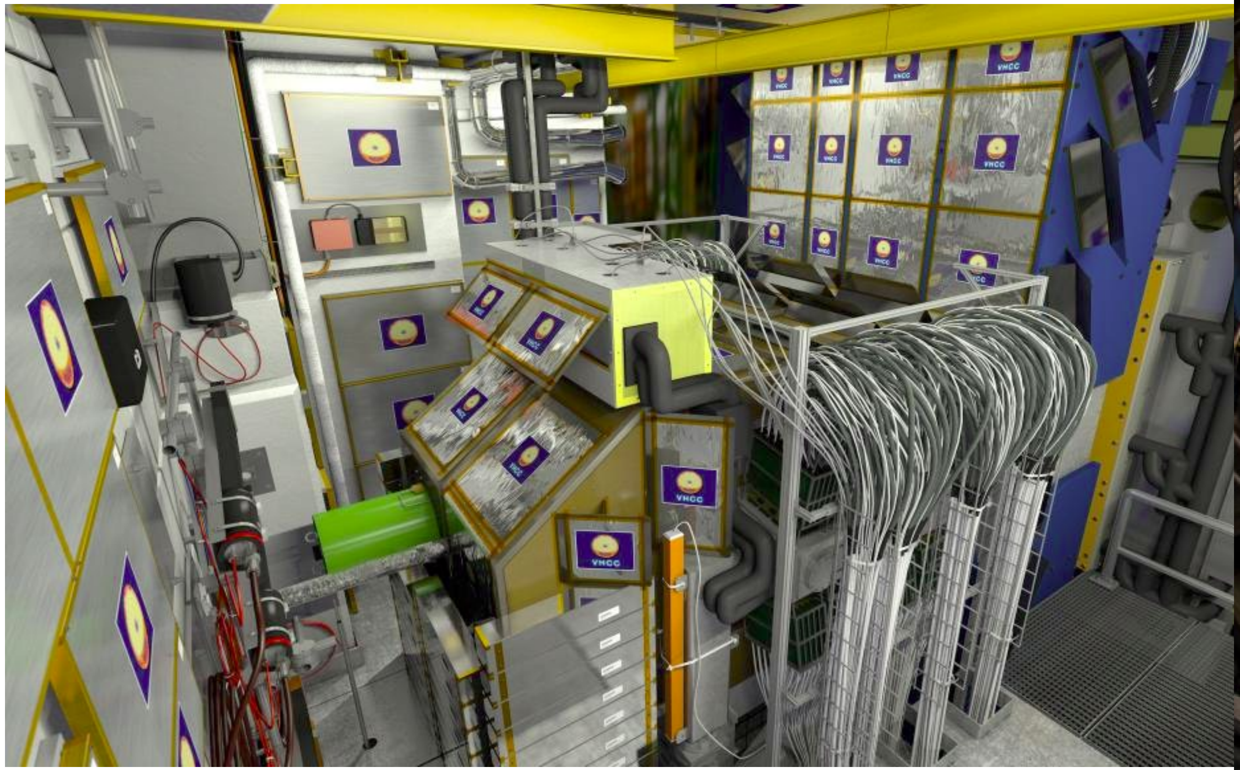
- The binding energies of magnetic monopoles in nuclei with large magnetic dipole moments estimated to be hundreds of keV *Nucl. Phys. B* ***255****, 465 (1985)*
- Close to 1 ton of Al MMTs deployed by MoEDAL
- After exposure, the MMTs are analyzed by a SQUID at ETH Zurich

# 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



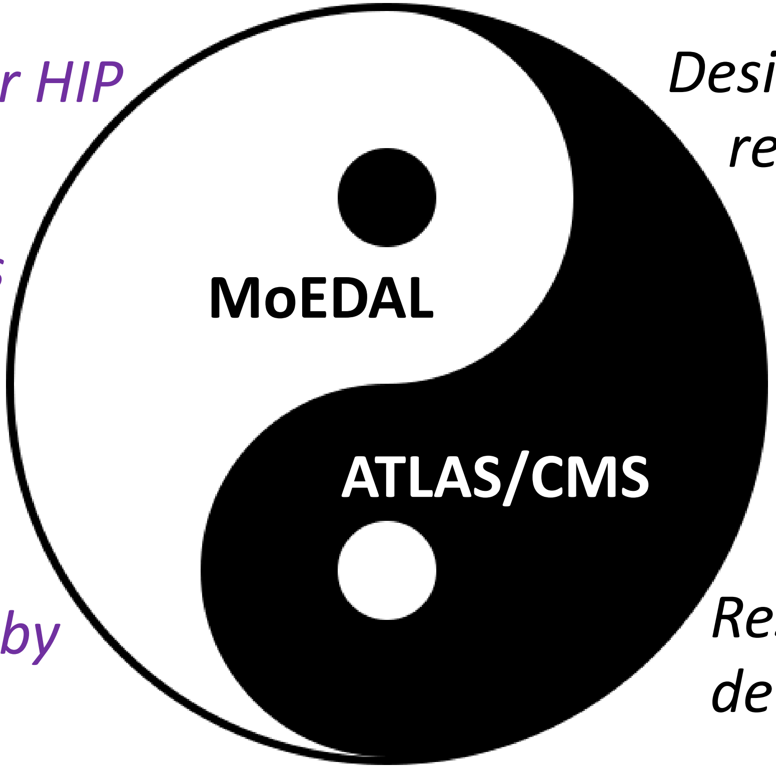
# Complementarity

*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*

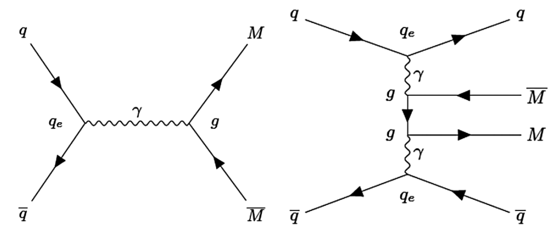
*Can infer magnetic charge from tracking and dE/dx*

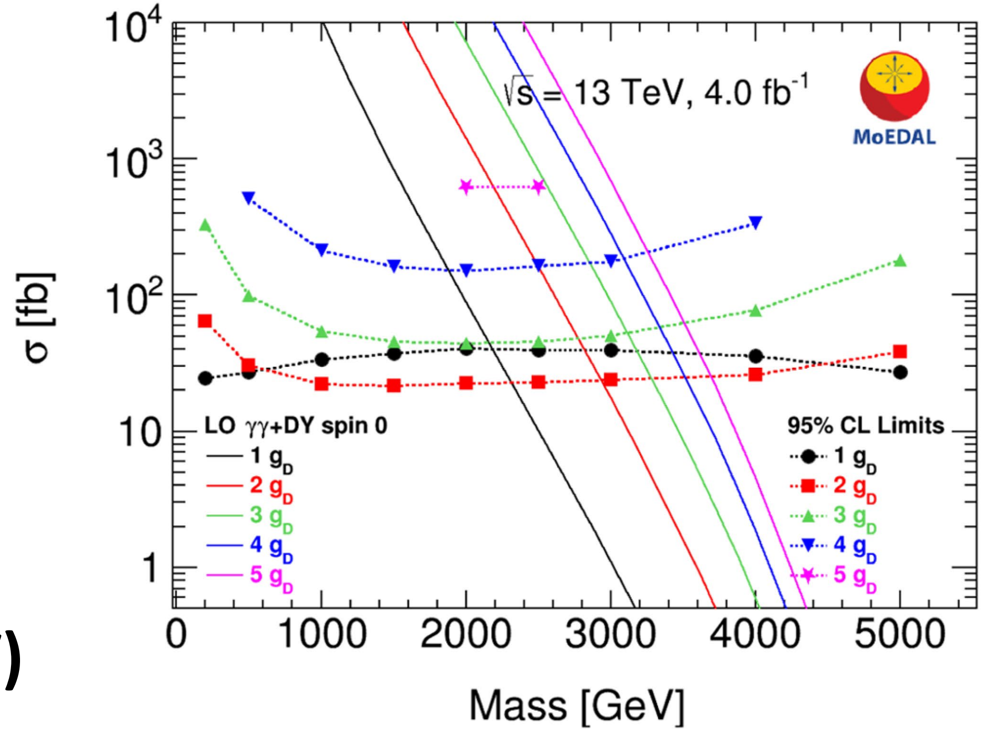
*Response estimated from detailed Monte Carlo*

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

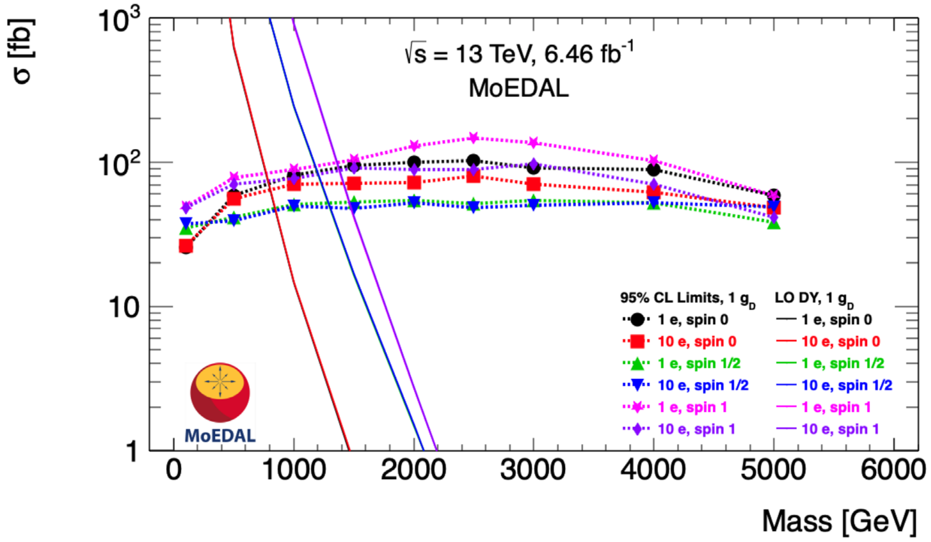
# Recent Results

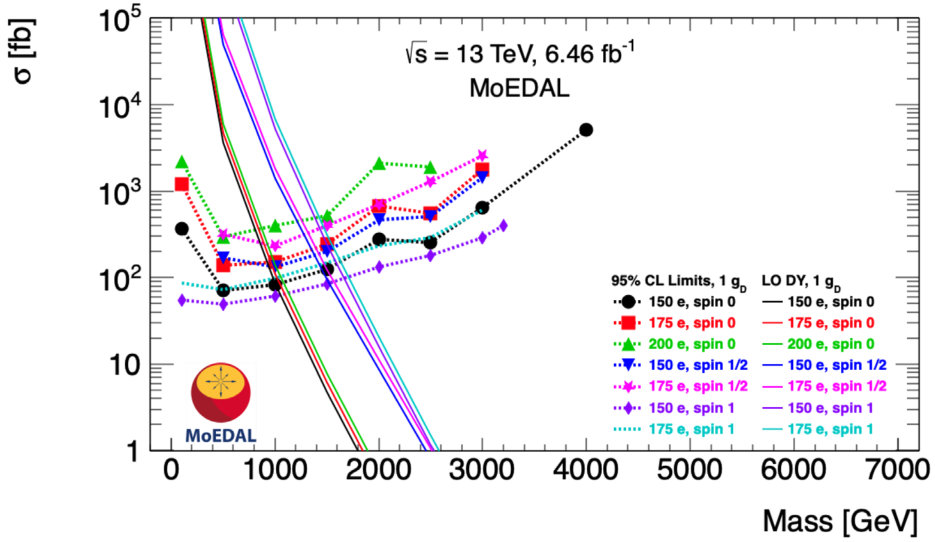
- "Magnetic monopole search with the full MoEDAL trapping detector in 13 TeV pp collisions interpreted in photon-fusion and Drell-Yan production"
  - *Phys. Rev. Lett.* ***123****, 021802 (2019)*
- For the first time at the LHC, monopoles were searched for via photon-fusion mechanism (in addition of Drell–Yan)
- **Best cross section limits $g > 2g_D$**
- **World leading mass limits (1.5–3.75 TeV) on magnetic charges $g > 2g_D$**





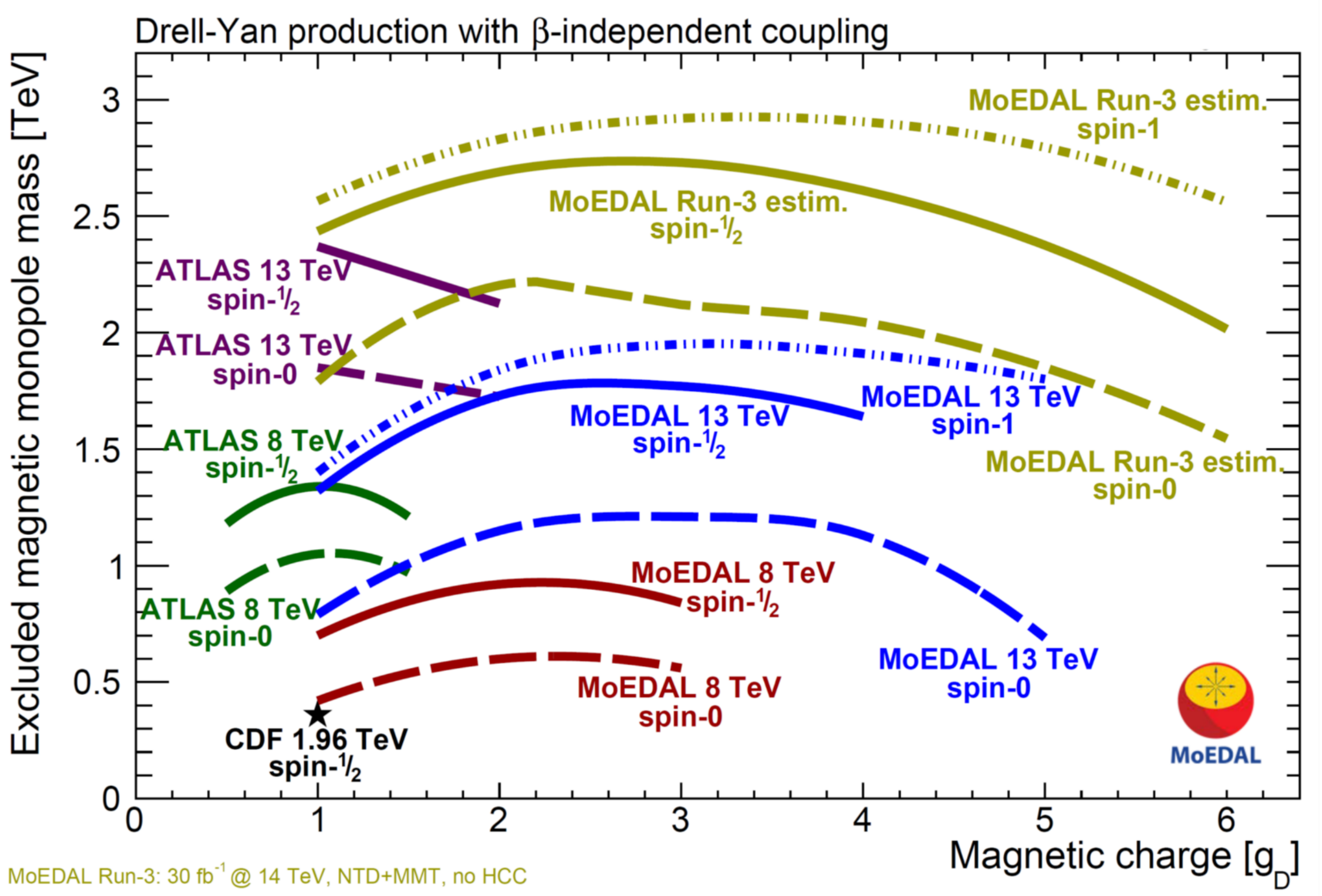
# Recent Results



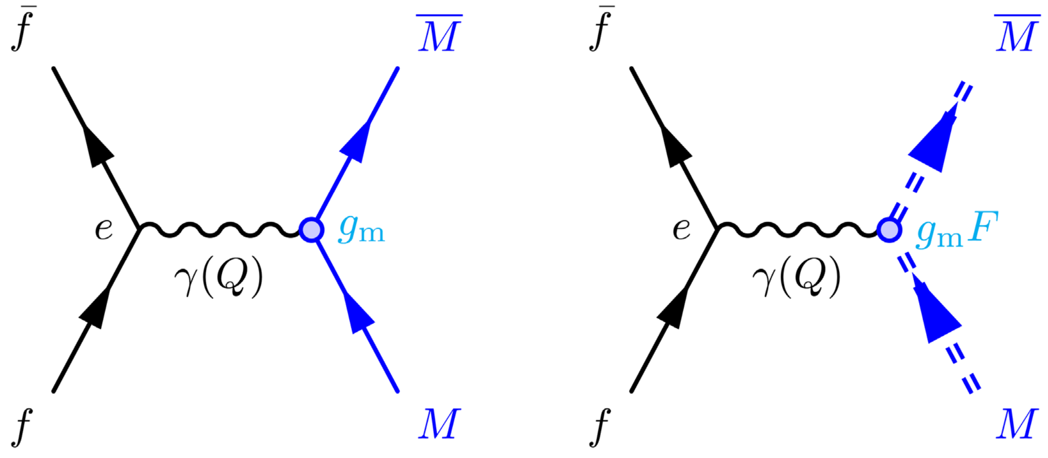




- "First search for dyons with the full MoEDAL trapping detector in 13 TeV pp collisions"
  - *Phys. Rev. Lett.* ***126****, 071801 (2021)*
  - **Mass limits 0.79–1.91 TeV on dyons with up to 5$g_D$ magnetic and 1$e$ – 200$e$ electric charges**

# State of the field for MM searches and projection for Run-3



# 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

*"Caveat on the caveat": purely nonperturbative treatment, which is lacking, may potentially lead to a different conclusion

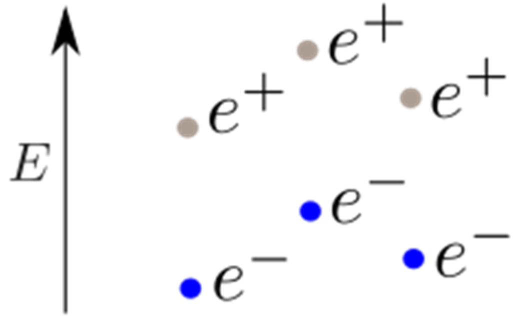
# The Schwinger mechanism

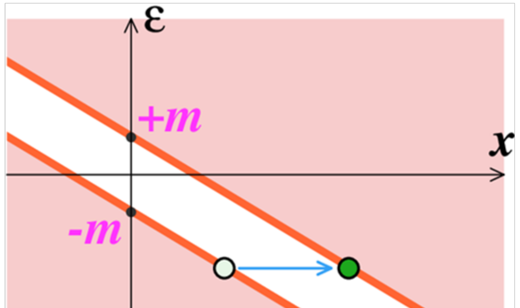
- Spontaneous creation of electron–positron pairs in presence of an extremely strong electric field
  - $E_s = \frac{m_c^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18}\, V/m$
- Due to the inherent instability of QED vacuum in presence of a strong electric field
  - Pair production originates from the 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)

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



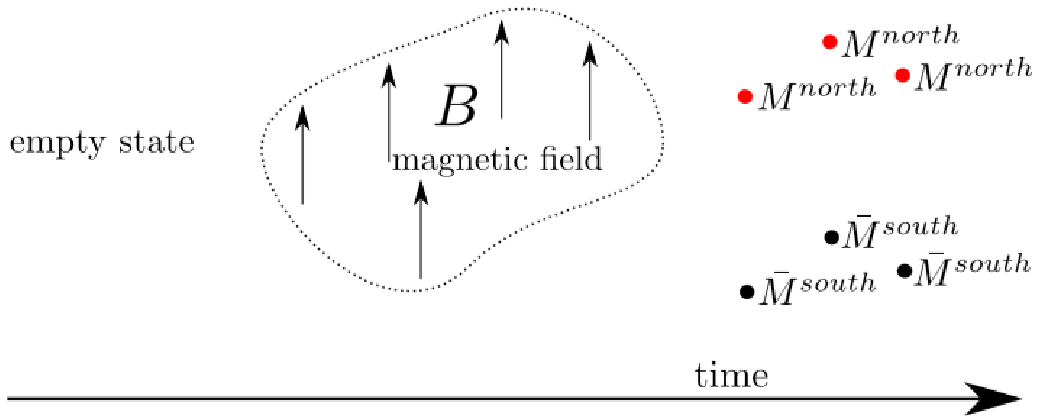



*Prog, Part. Nucl. Phys.* ***87****, 1 (2016)*

# 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!

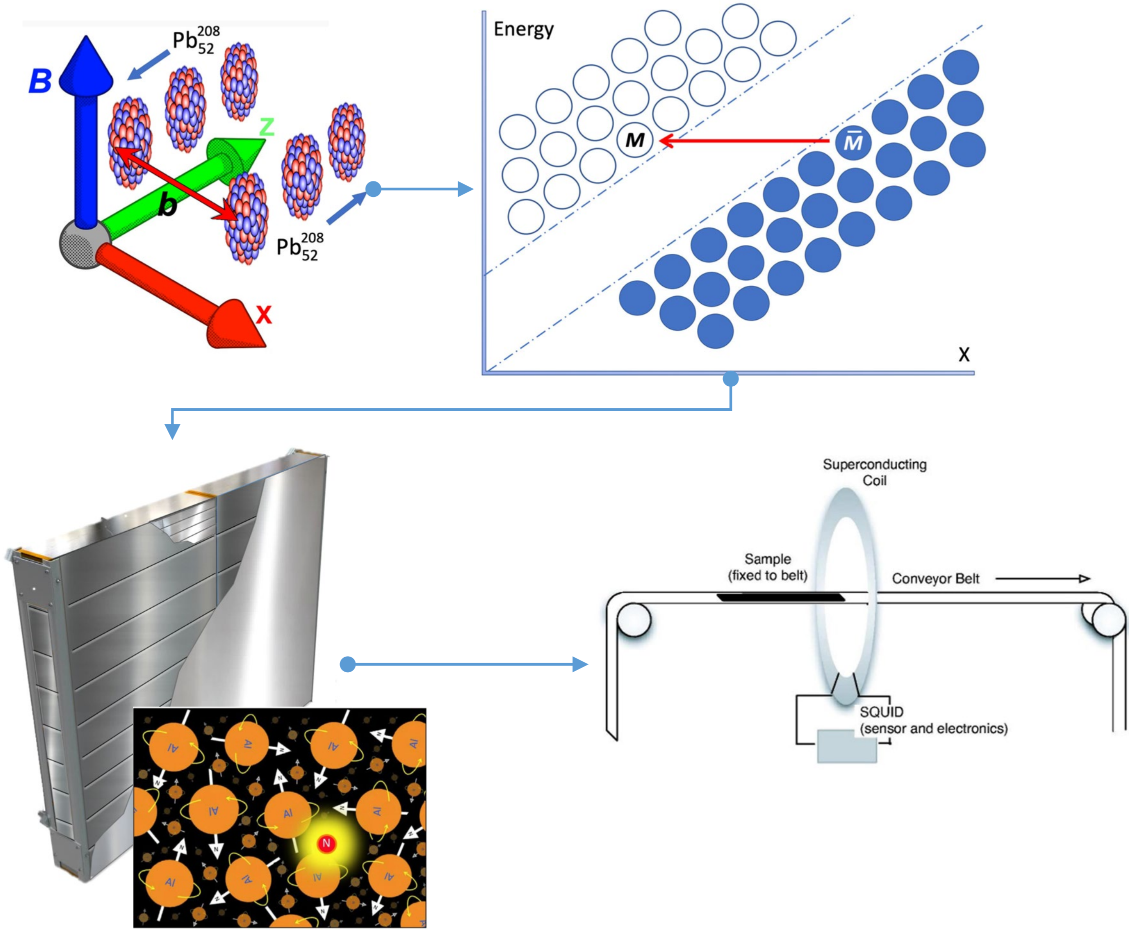
Strong magnetic fields can produce magnetic monopoles.




*Nucl. Phys. B 194, 38 – 64 (1982)*

# MoEDAL search for Schwinger monopoles

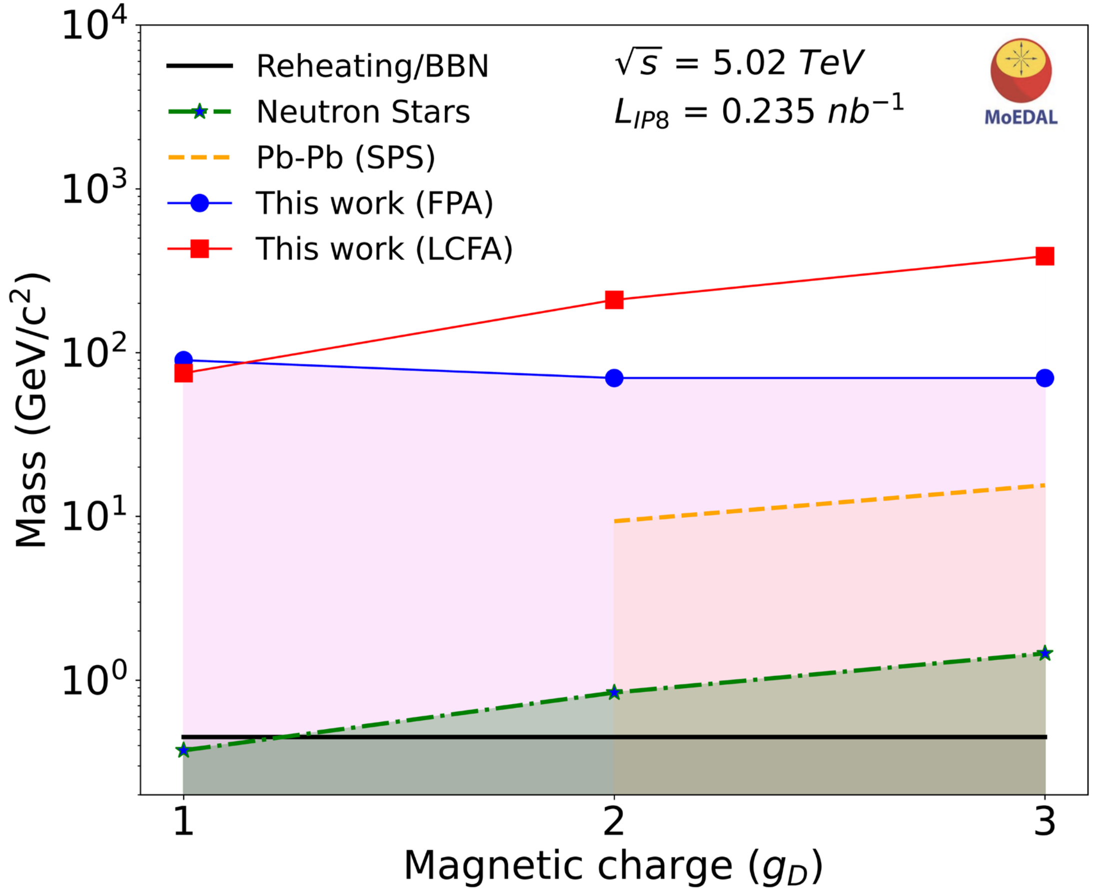
- The 2018 LHC heavy-ion run
  - Relativistic, bare Pb nuclei, $\gamma$ = 2675
  - CM energy of 5.02 TeV per collision
  - Ultra-peripheral collisions with $B_{peak}$ ~ $10^{20}$ G and $\omega$ ~ $10^{26}$ $s^{-1}$ (inverse decay time)
- 880 kg of MoEDAL's MMTs exposed to integrated luminosity of 0.235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



# Results of the search

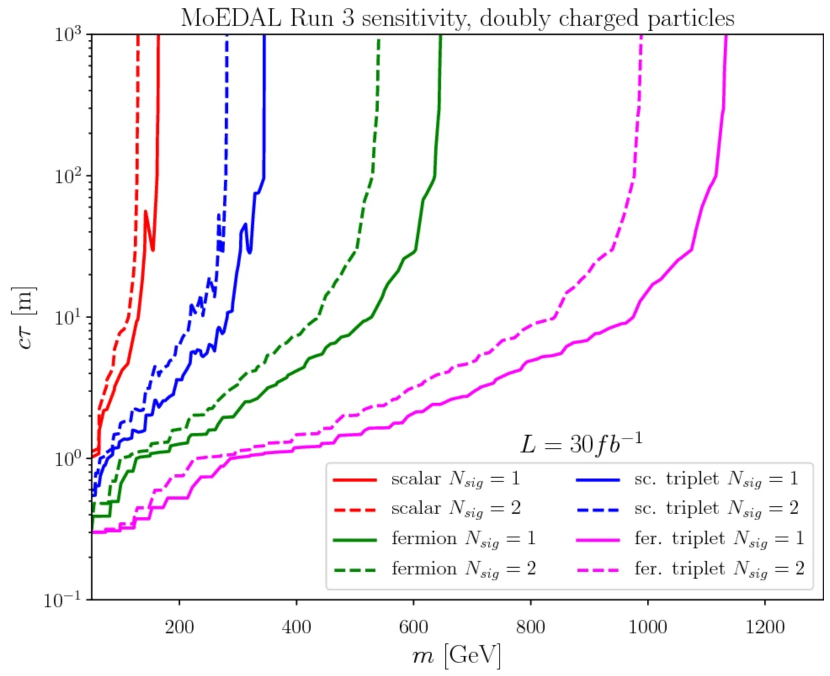
- No statistically significant signal was observed
- The existence of a monopole with $g > 0.5g_D$ in the trapping volume was excluded at more than $3\sigma$
- First reliable limits on monopole mass
  - Based on nonperturbative cross section calculation
  - No suppression for composite monopoles
- For more details of this search, see the Aditya Upreti's poster!

Nature 602 (2022) 7895, 63-67



# Searches for other Exotics with MoEDAL

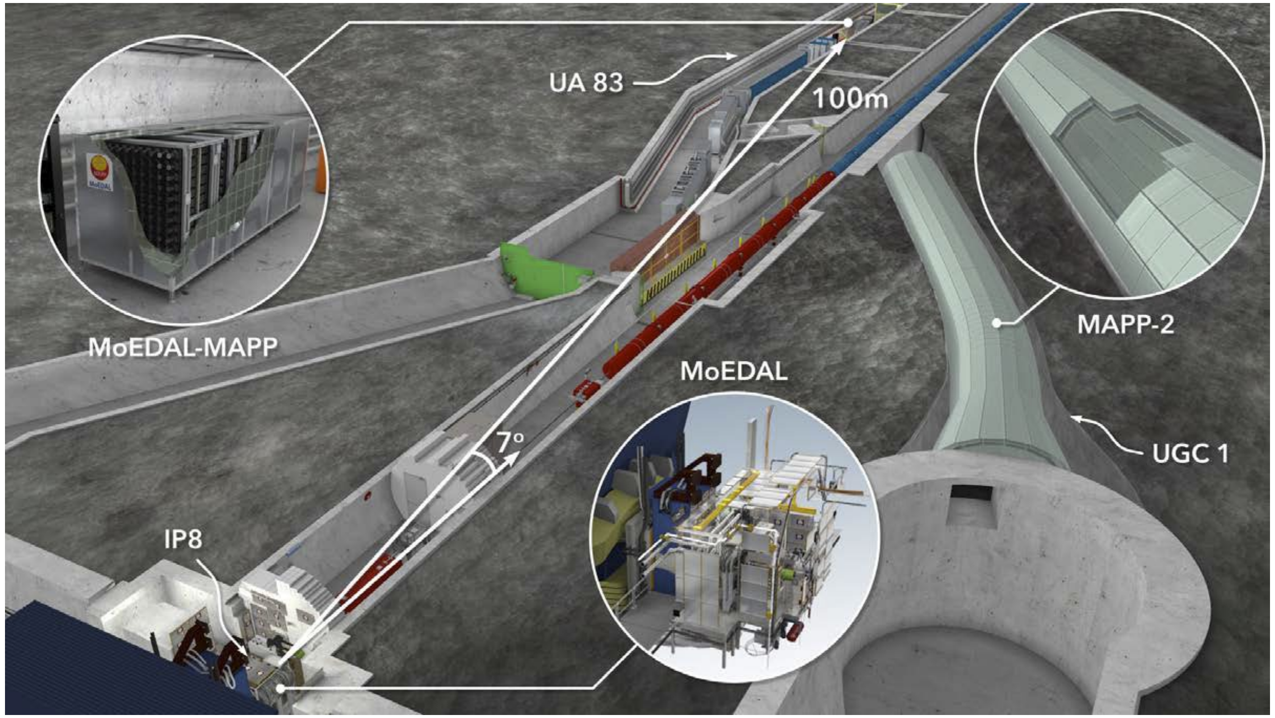
- MoEDAL NTDs are also sensitive to highly electrically charged objects (HECOs) that may include aggregates of quark matter, Q-balls, or micro black hole remnants
  - First paper on Run-1 dataset has been published in EPJC in 2022
- If sufficiently slow-moving, even singly or multiply ($\lesssim 10$) 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)*

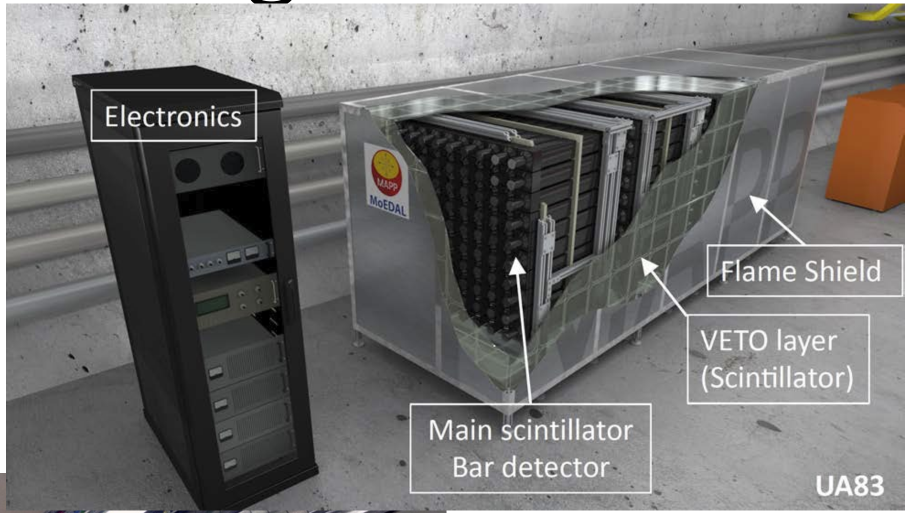
# MoEDAL Apparatus for Penetrating Particles

- 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

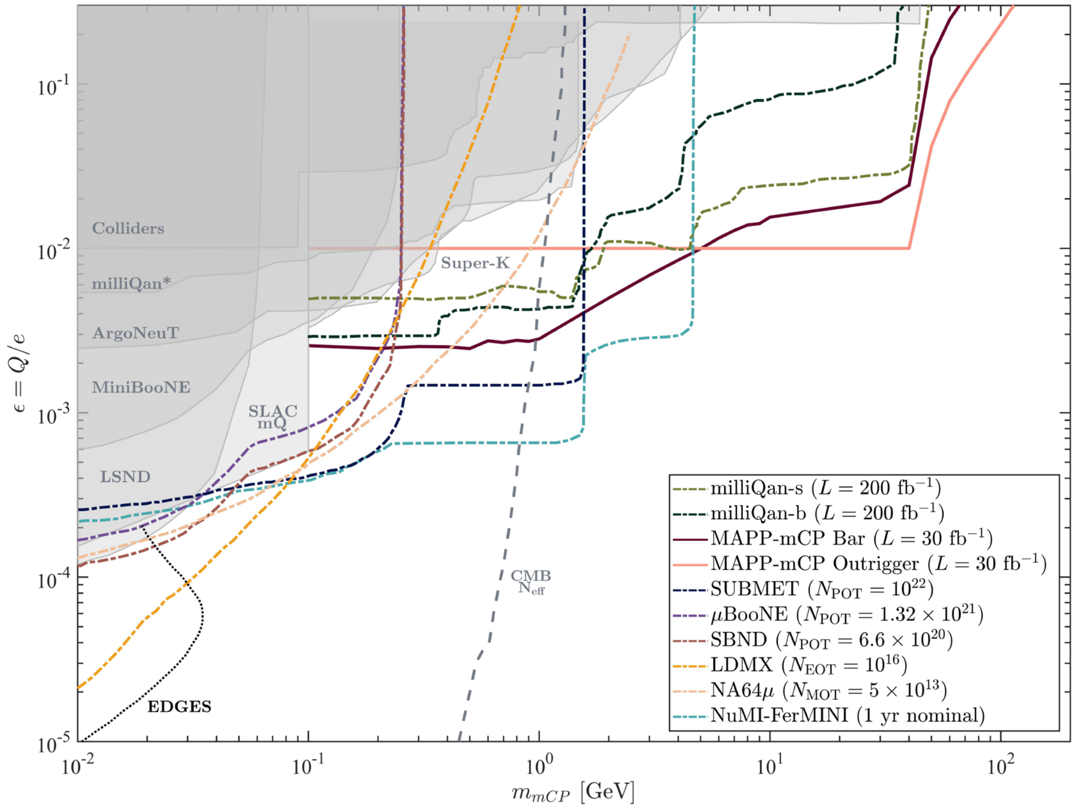
- Detector consists of 4 sections with 10×10 array of 100 scintillator bars each
  - Protected by a hermetic VETO counter system
  - Each through-going particle sees 3 m of scintillator readout by a coincidence of 4 low noise PMTs
  - Being installed in UA83, ~100 m from the IP8




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

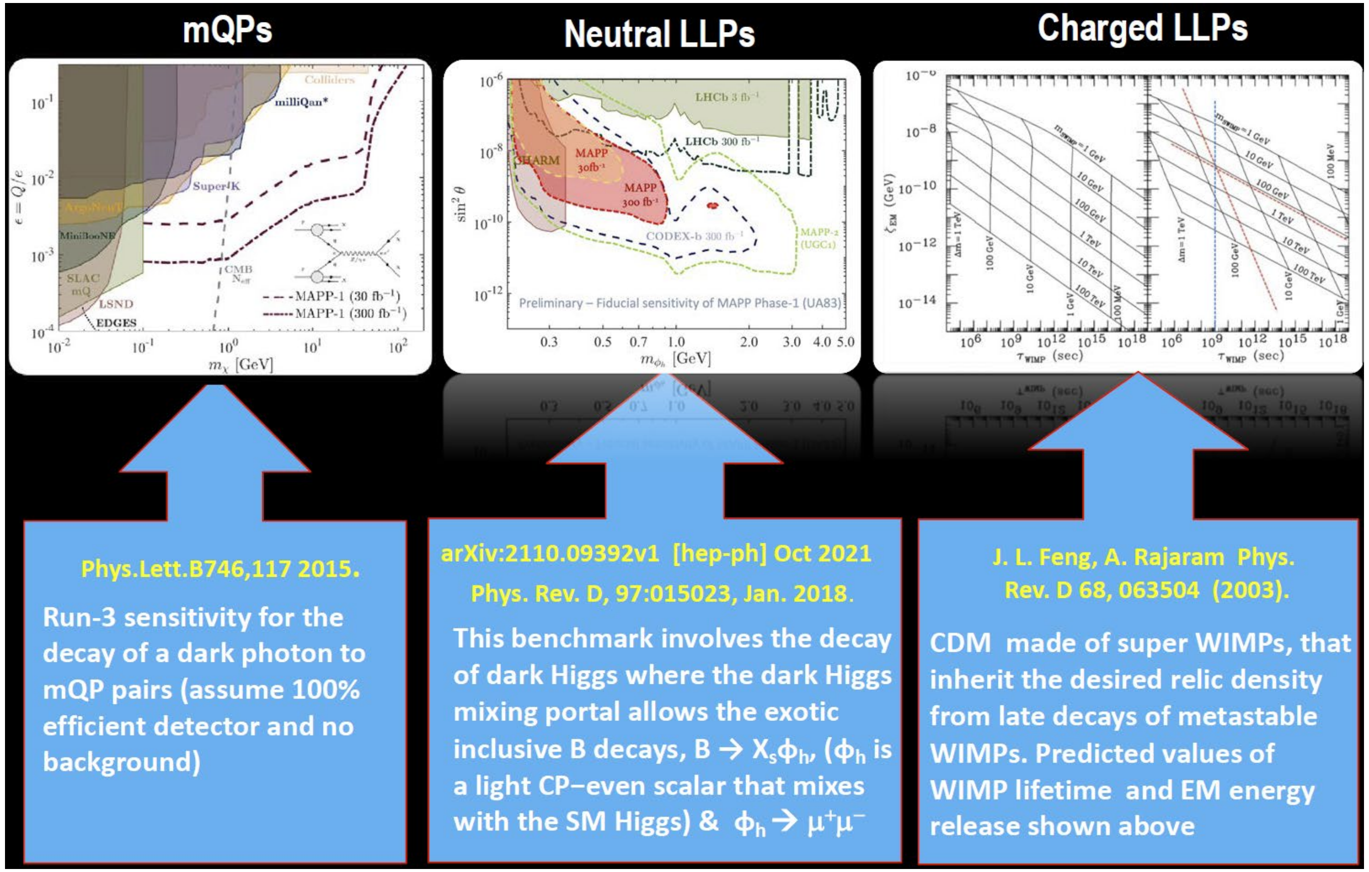



Existing bounds and projected sensitivity for mQPs, for models with a massless dark photon

# 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

# MAPP physics program



# CMS Run-1 beampipe

# 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 $\geq 2g_D$

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 ~ $9.3 \times 10^3 - 2.3\ 10^4$ 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

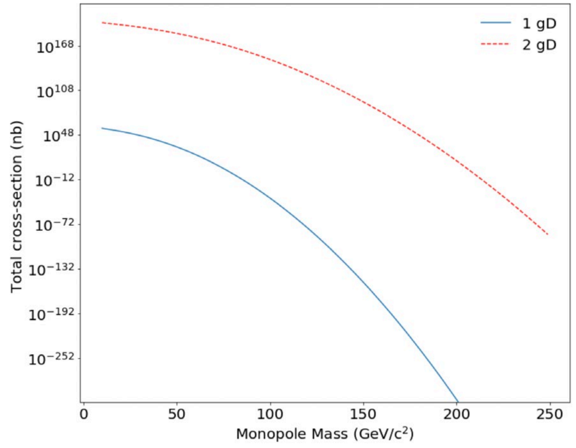
P.Q. Hung, arXiv:2003.02794
***(Nucl.Phys.B* 962 (2021) 115278)**

**Hung, Ellis, NEM, arXiv: 2008.00464**

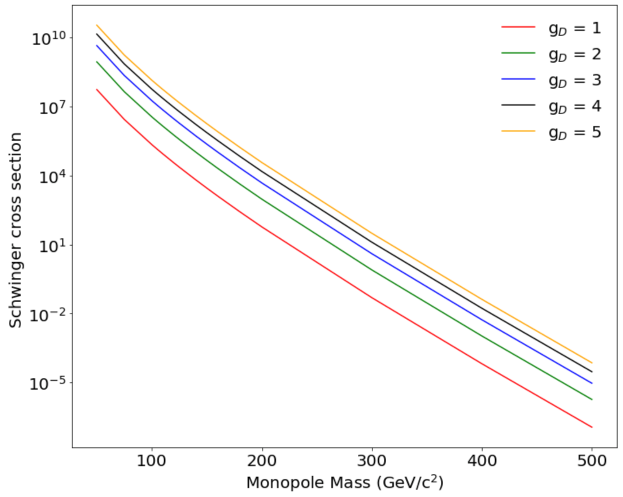
# Two cross section approximations

- 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

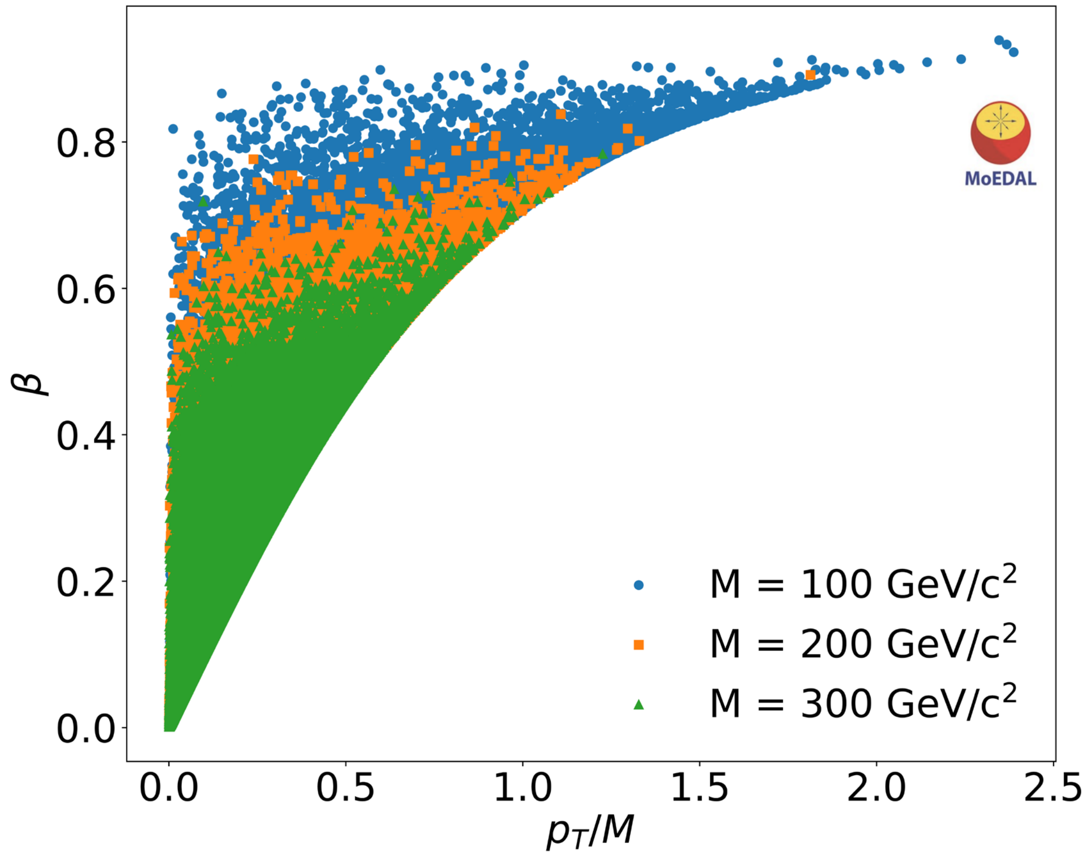


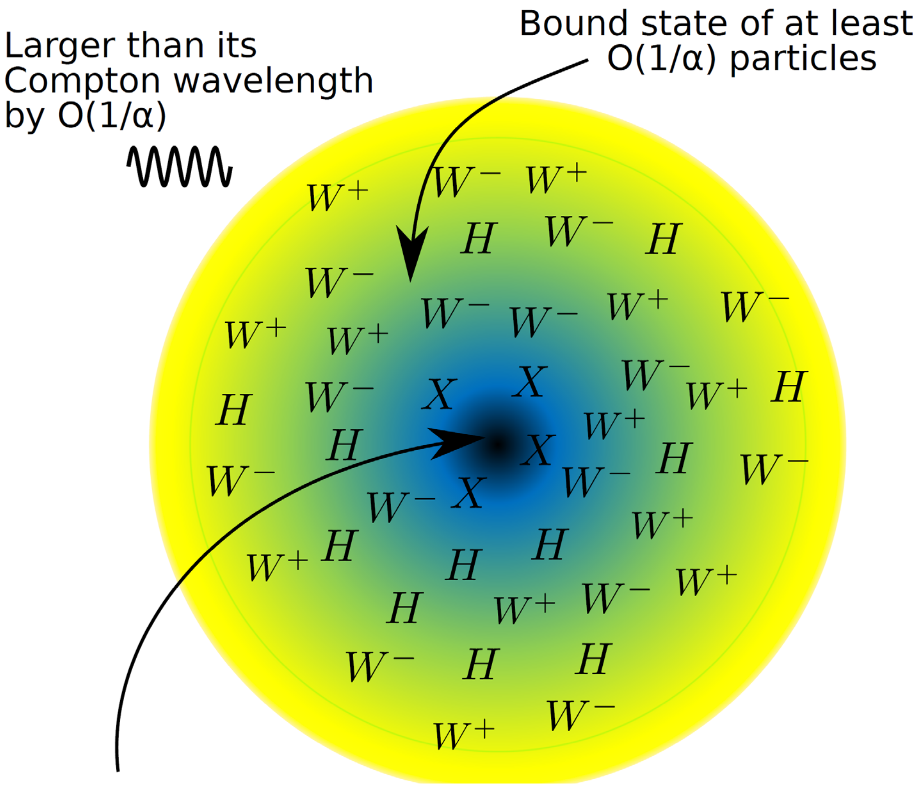

FPA



# 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)*

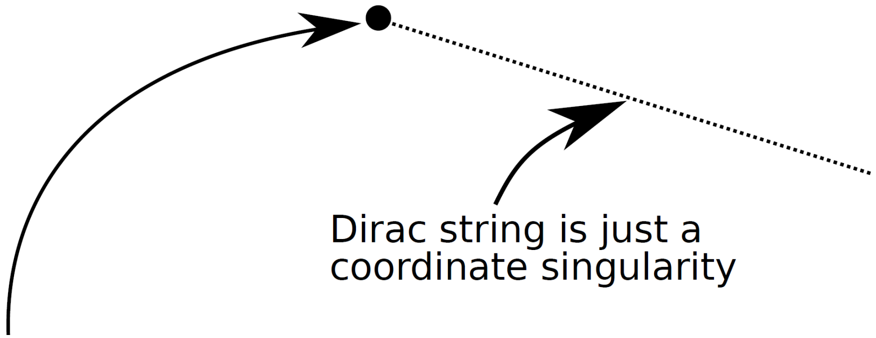




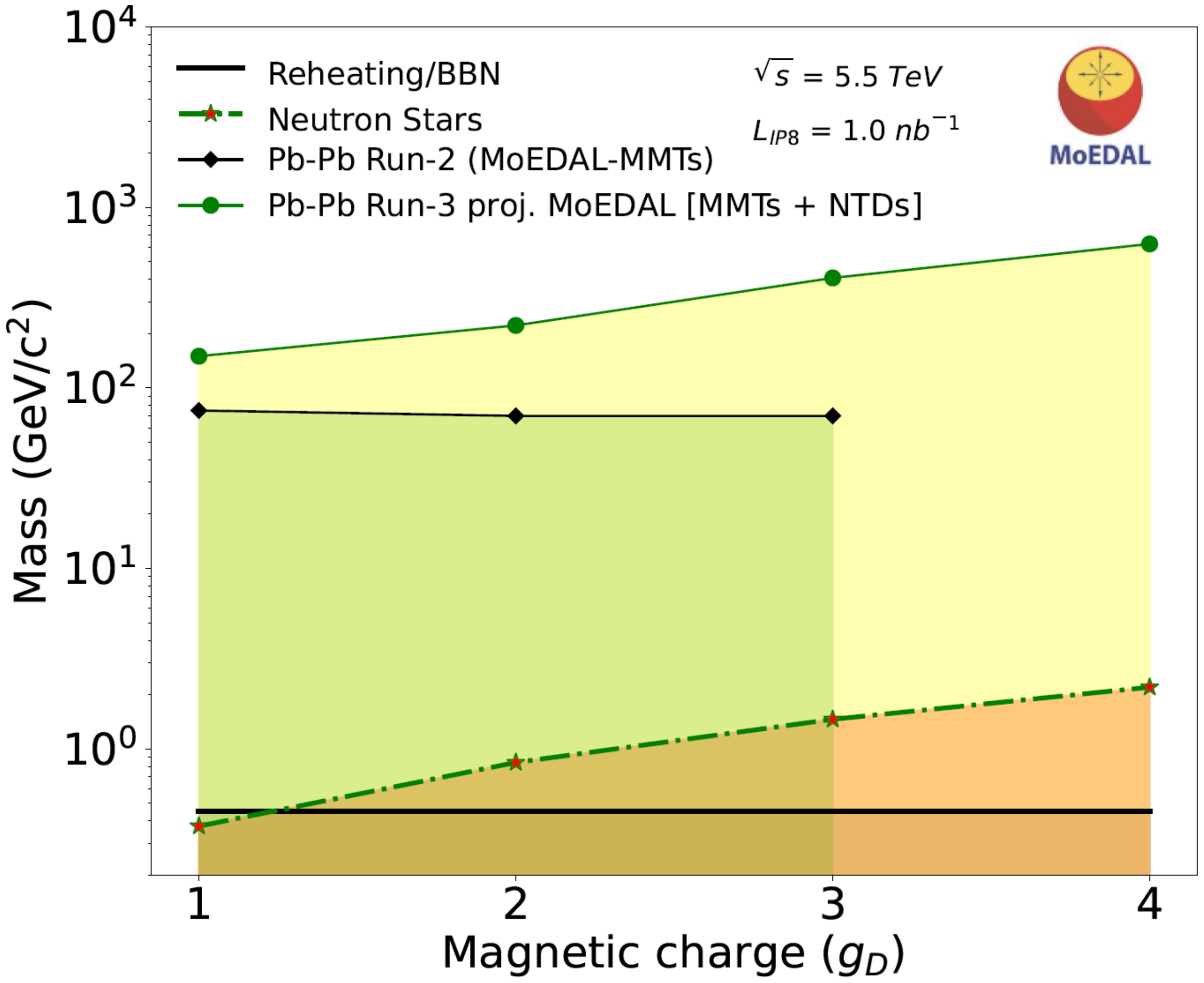

Composite

Consistent QFT of elementary monopoles exists

Any mass is possible




Point-like



Reheating/BBN
Neutron Stars
Pb-Pb Run-2 (MoEDAL-MMTs)
Pb-Pb Run-3 proj. MoEDAL [MMTs + NTDs]
$\sqrt{s}$ = 5.5 TeV
$L_{IP8}$ = 1.0 $nb^{-1}$
MoEDAL
Mass (GeV/c$^2$)
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
1
2
3
4
Magnetic charge ($g_D$)