Searching for the Schwinger Production of Magnetic Monopoles in Pb-Pb Collisions at the LHC

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on behalf of the MoEDAL collaboration

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)*

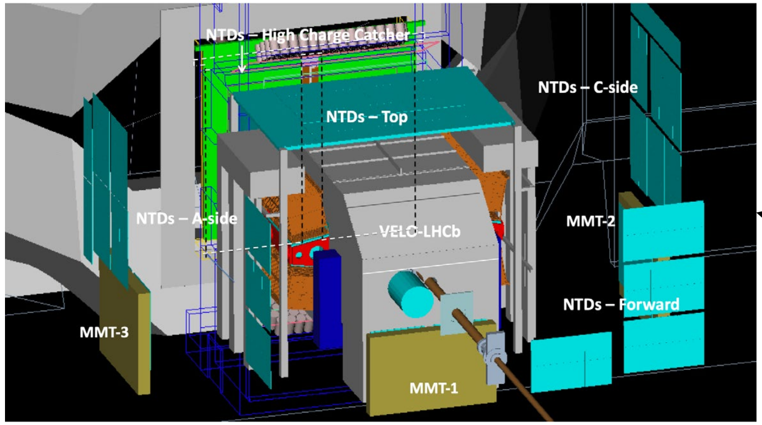
- Mass is a free parameter. While the GUT scale monopole (~10^{16} GeV) received the most interest earlier, several recent models point to possibility of monopoles with masses **accessible at the LHC**

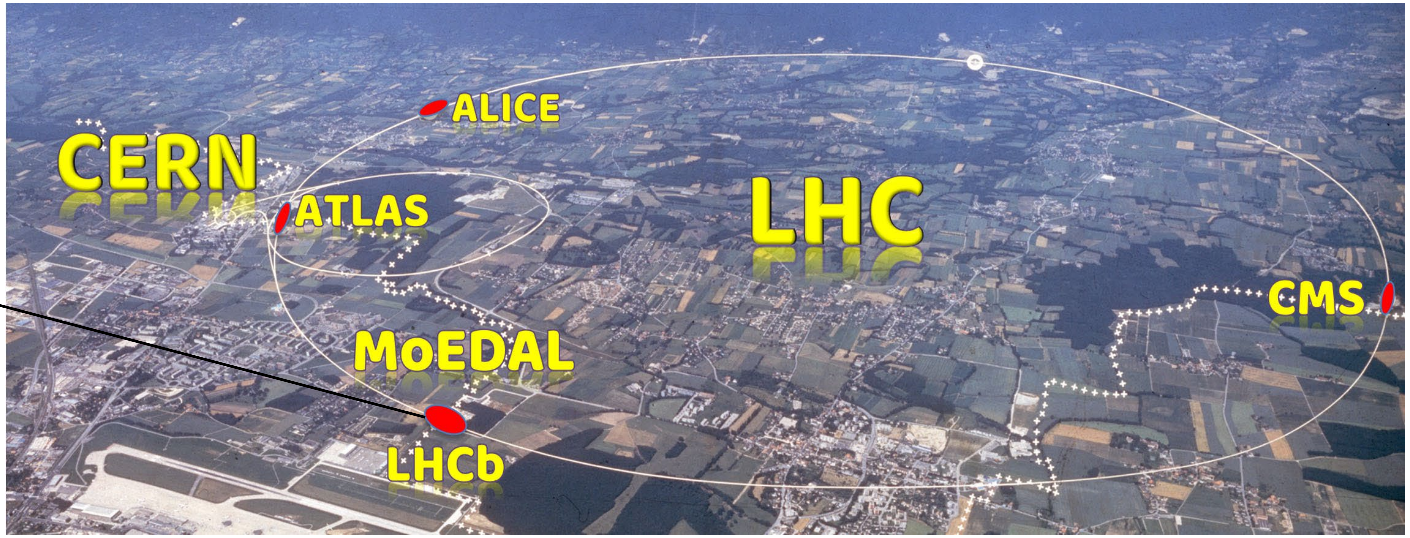
  *EPJC **75**, 67 (2015), Nucl Phys B **969** 115468 (2021)*

Magnetic Monopole's basic properties

$e \cdot g_D = \frac{\hbar c}{2} n \rightarrow g_D = \frac{n}{2\alpha} e \Rightarrow$ $\mathbf{1}\boldsymbol{g_D} = \mathbf{68.5} \cdot \boldsymbol{e}$	• If fundamental charge is $e/3$, then $g_M = 3g_D$
$\boldsymbol{\frac{g_D^2}{\hbar c} \sim 34}$	• 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**
$\boldsymbol{-\frac{dE}{dx} \sim \frac{Z}{A} g_M^2 \cdot \left[\ln\left(\beta^2\gamma^2\right) + \ \ldots\right]}$	• Fast monopoles are highly ionizing! $\frac{dE}{dx} \sim g_M^2$= **4700 MIP** for $1g_D$ • Ionization of g_M **increases with β**, as opposite to e

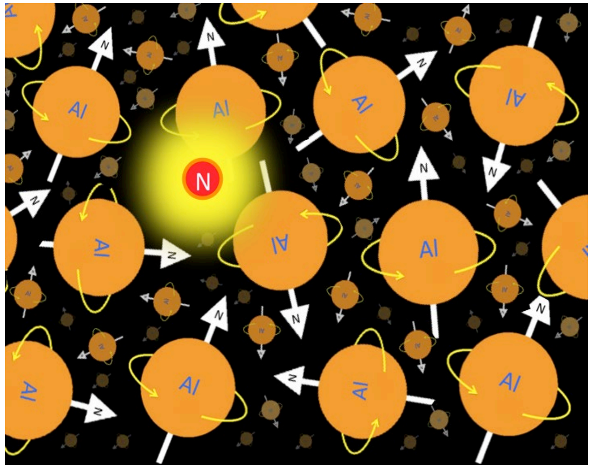
MoEDAL – dedicated search at the LHC

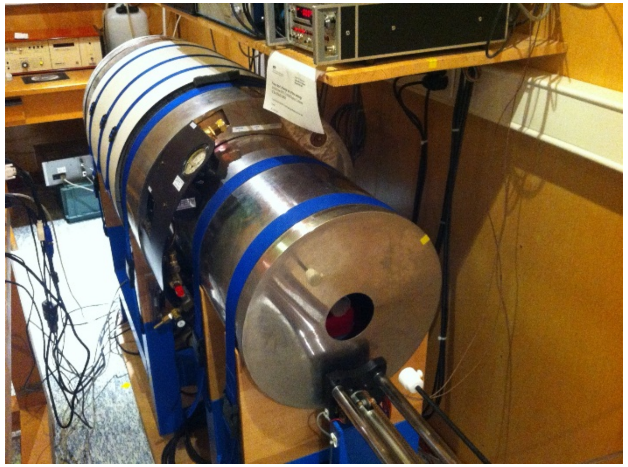




- "Monopole and other Exotics Detector At LHC" optimized to search fo **magnetic monopoles** and other highly ionizing particles with magnetic and/or electric charge (dyons, nuclearites, Q-balls,)
- 67 physicists from 24 institutions. Approved by CERN 2009, started data-taking Spring 2015
- Deployed 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
  - First search for dyons, First search using $\gamma\gamma$ fusion production model
  - See talks by R. Soluk and J. Pinfold for more details and plans for MoEDAL extension in Run-3

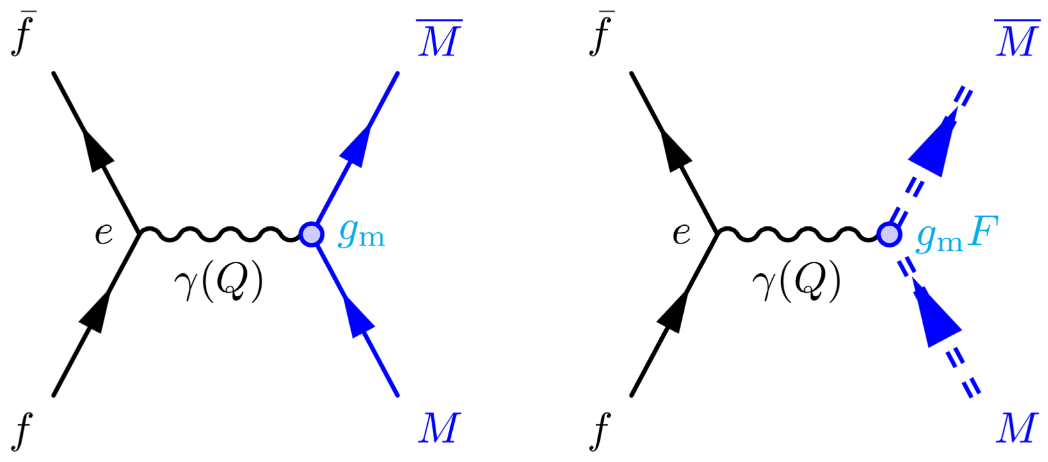
MMT





- 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

Difficulties with collider searches



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

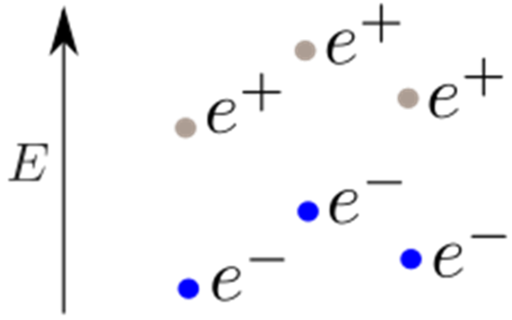
The Schwinger mechanism

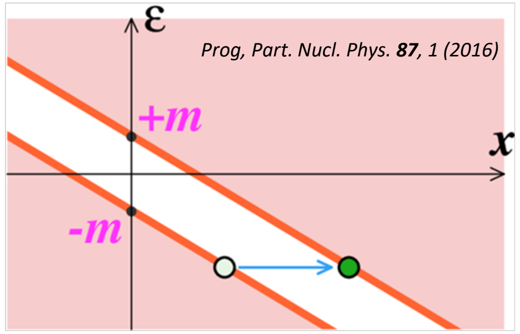
- Spontaneous creation of electron–positron pairs in presence of an extremely strong electric field
  - $E_s = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18}\, V/m$
- Due to the inherent instability of QED vacuum in presence of a strong electric field
  - Pair production originates from the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

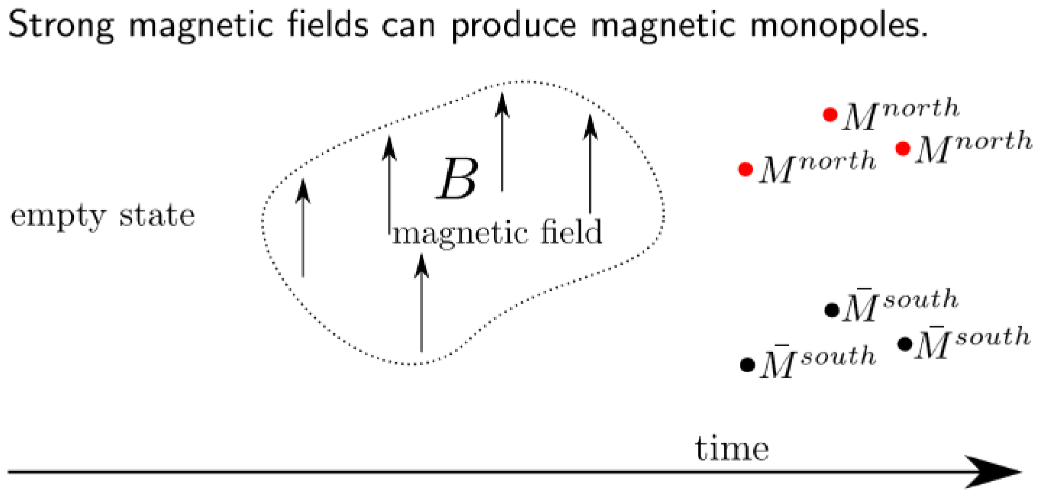
$$\Gamma = \frac{(eE)^2}{4\pi^3 c\hbar^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\frac{\pi m^2 c^3 n}{eE\hbar}}$$





The Schwinger mechanism at the LHC

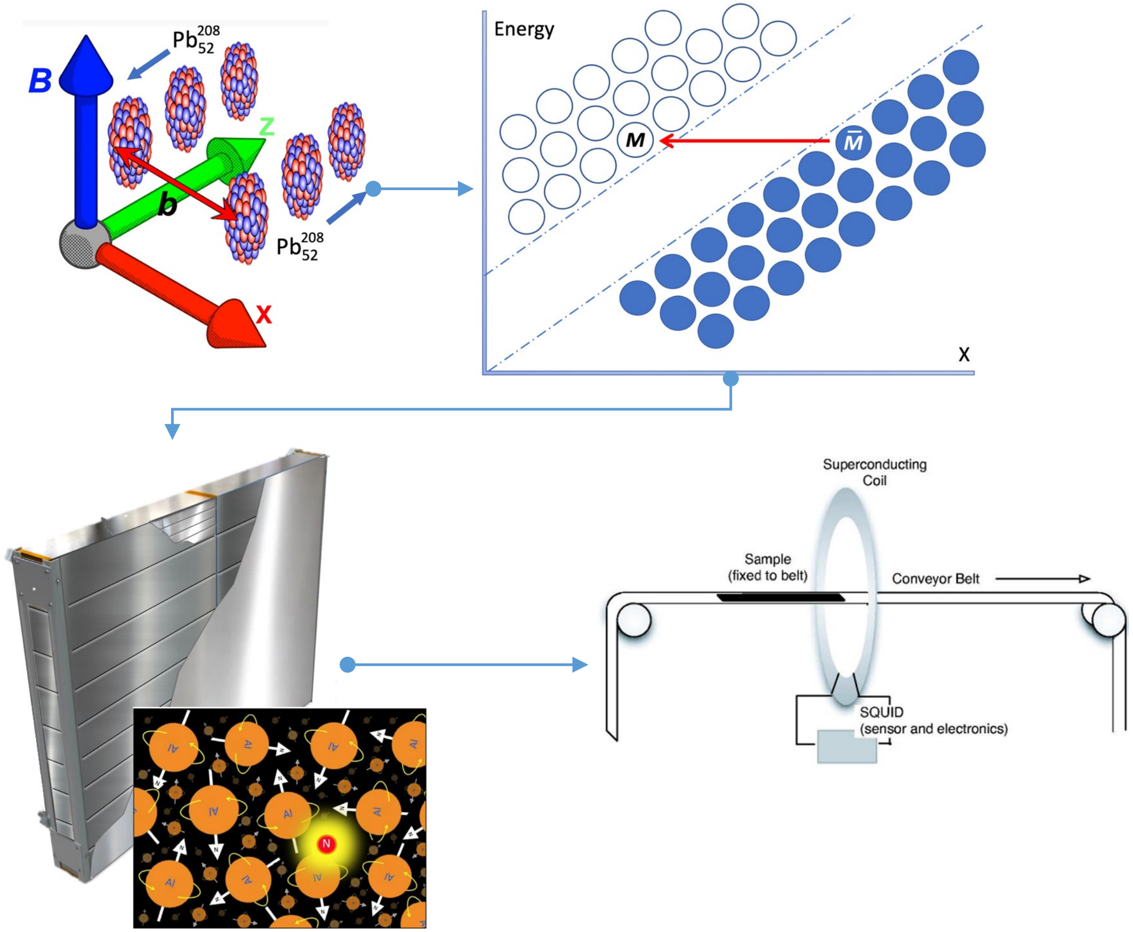
- By electromagnetic duality, a strong magnetic field would produce monopoles via the same mechanism
- Ultraperipheral Pb-Pb collisions at the LHC have produced the strongest peak magnetic fields in the known universe
  - **B ~ 10^{16} T, as compared to ~ $10^{11\text{-}12}$ T on a magnetar's surface**
- **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 (1982)*

MoEDAL search for Schwinger monopoles

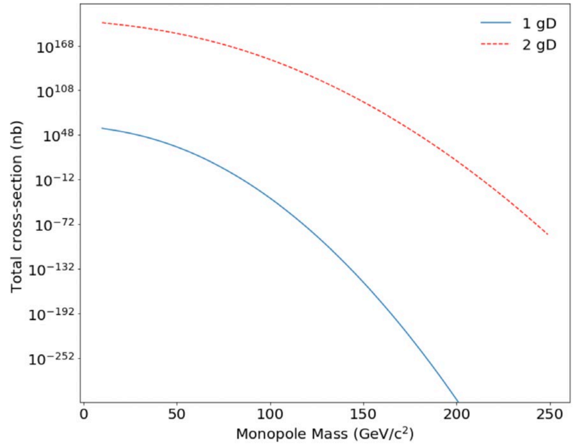
- The 2018 LHC heavy-ion run
    - Relativistic, bare Pb nuclei, γ = 2675
    - CM energy of 5.02 TeV per collision
    - Ultra-peripheral collisions with B_{peak} ~ 10^{20} G and ω ~ 10^{26} s^{-1} (inverse decay time)
- 880 kg of MoEDAL's MMTs exposed to integrated luminosity of 0.235 nb^{-1}
    -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



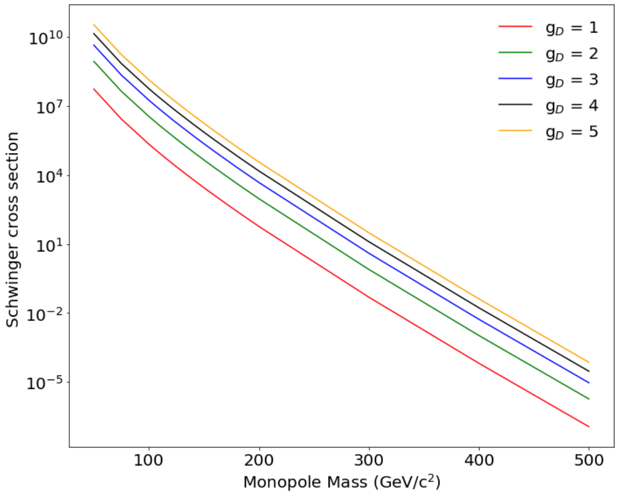
Two cross section approximations

- 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

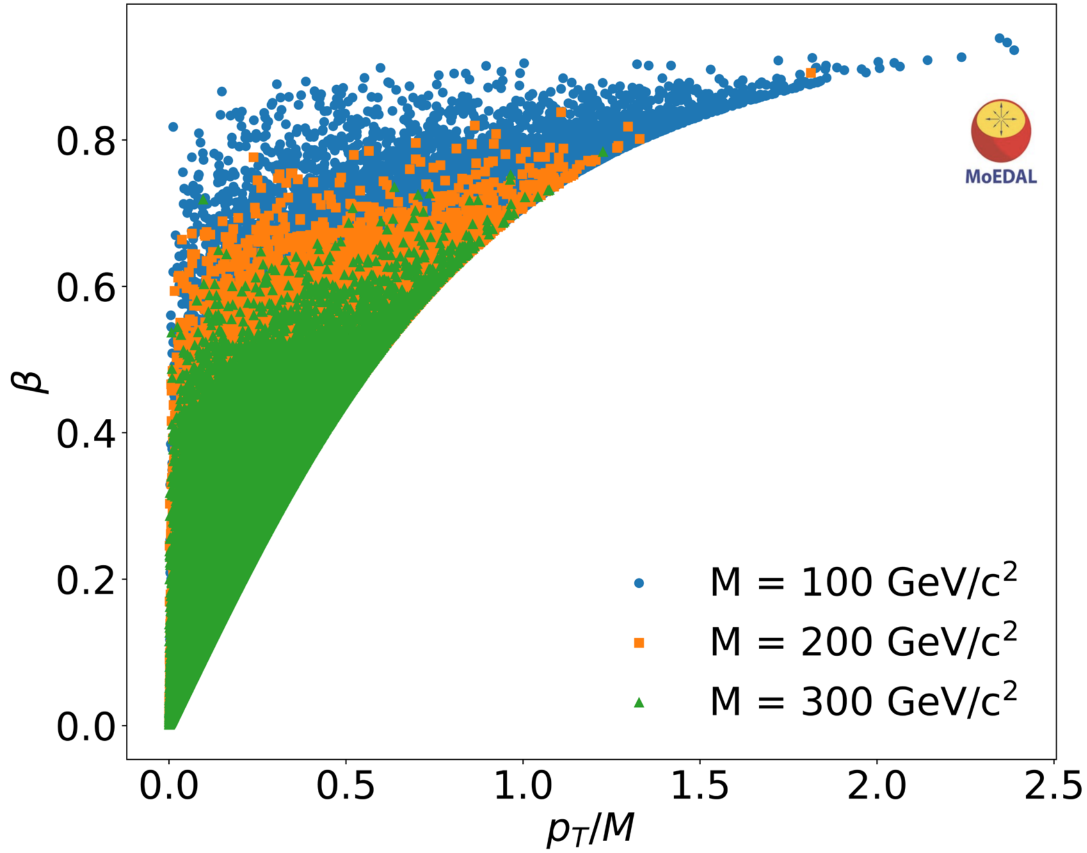


FPA

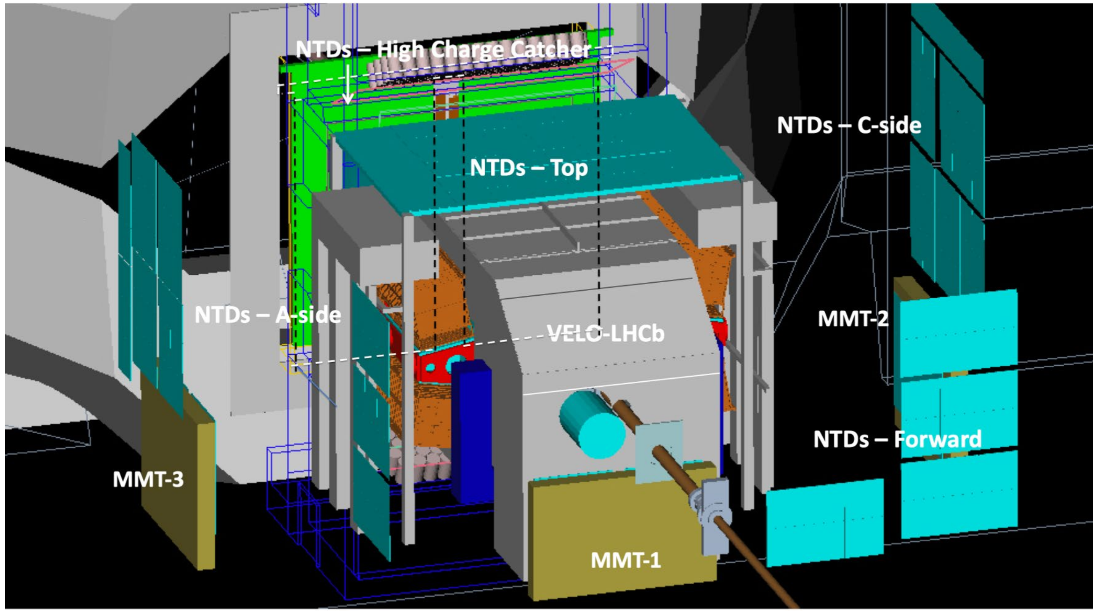


Kinematics

- 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)*



MoEDAL Monte Carlo simulation

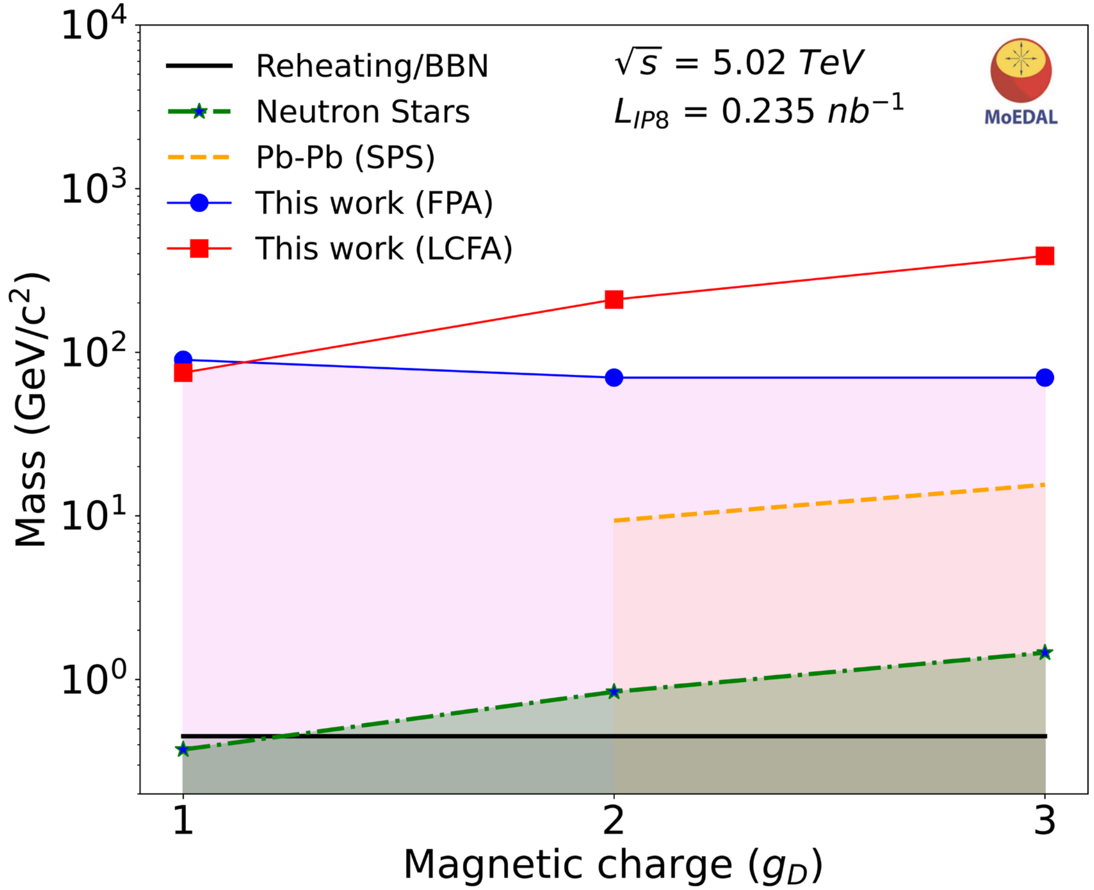


- Schwinger monopoles are generated in MC simulations using the FPA kinematic distribution
- The simulation code is developed in Gauss (LHCb's simulation framework) that uses Geant4 as the simulation engine
- MoEDAL added monopole physics, detailed experiment's geometry and material content
- Monopoles are propagated through the MoEDAL detectors, and the trapping efficiency is calculated
- **Combined with the luminosity and calculable cross section, the expected rate of trapped monopoles can then be predicted and compared to the observed number of isolated magnetic charge trapped in MMTs after the Pb-Pb run**

Results of the search

- No statistically significant signal was observed
- The existence of a monopole with $g > 0.5g_D$ in the MMTs was excluded at more than 3σ
- First reliable limits on mass: <75 GeV for 1 – 3 gD monopoles
  - Based on nonperturbative cross section calculation
  - No suppression for composite monopoles

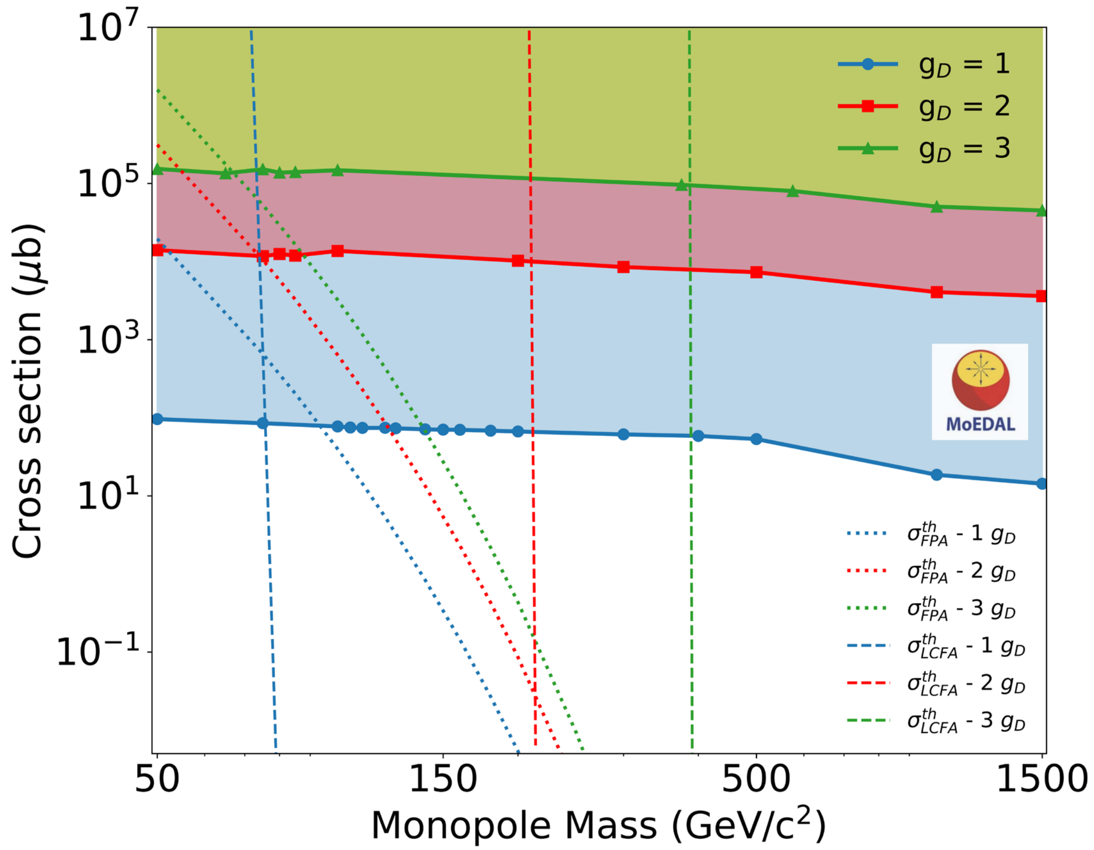
[Nature 602 (2022) 7895, 63-67]



Results of the search

Nature 602 (2022) 7895, 63-67

- Alternatively, can interpret the results as experimental limits on Schwinger production cross section (assuming FPA kinematics)

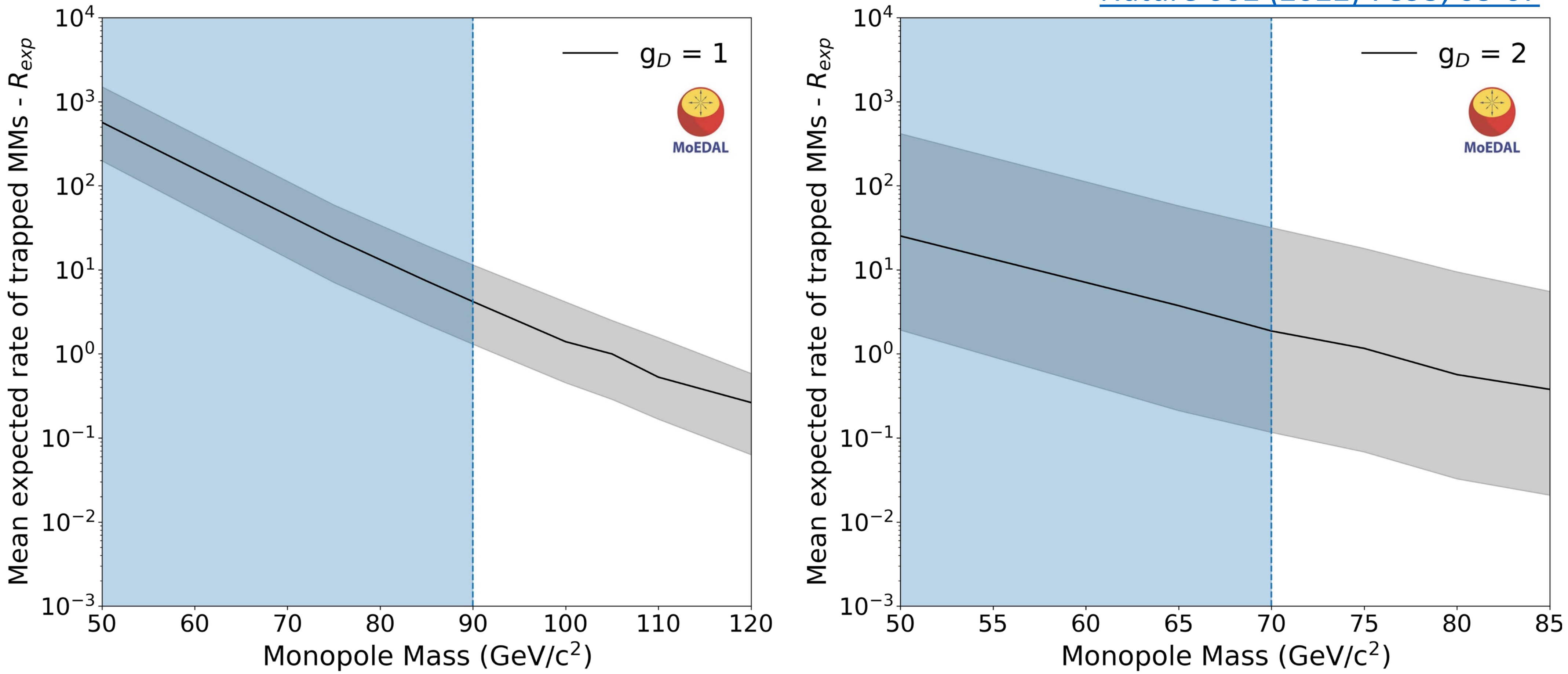


Summary

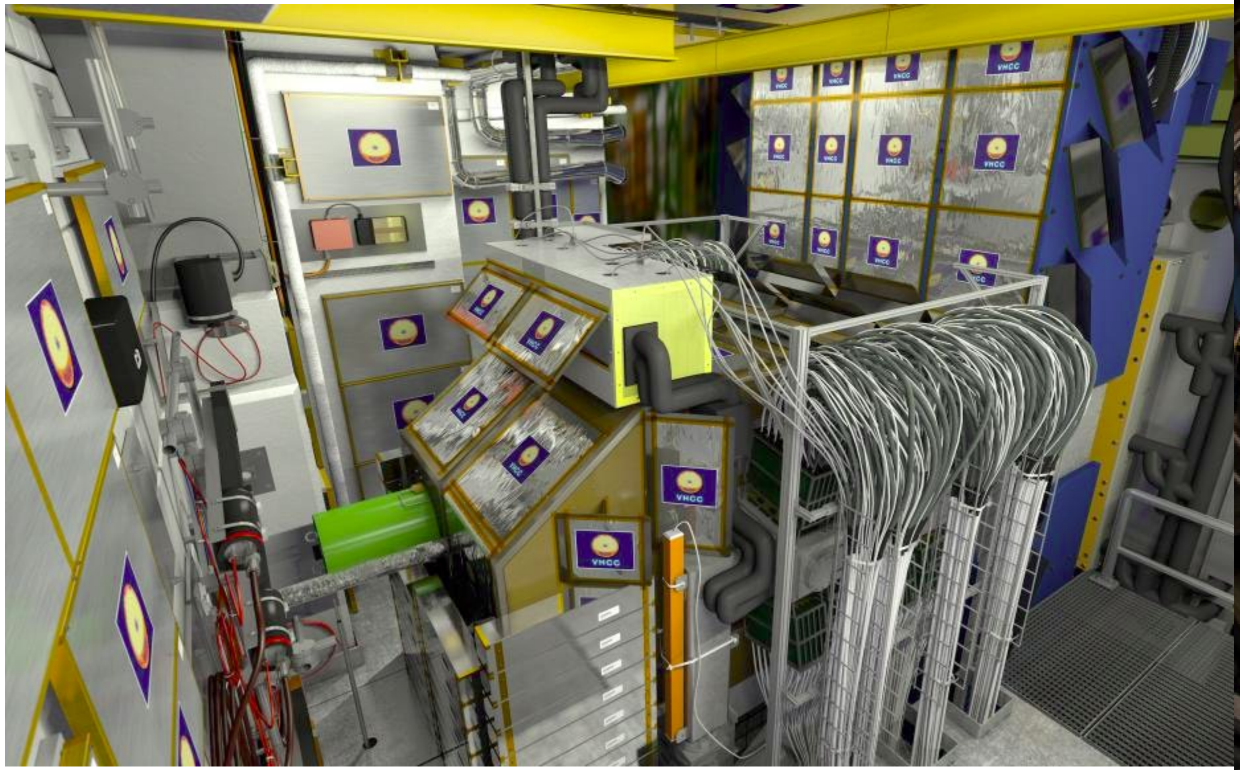
- The existence of magnetic monopoles is well motivated, but their mass and production mechanism are uncertain
- MoEDAL is a dedicated search for magnetic monopoles and other exotic particles at the LHC that established world-leading limits on production of monopoles and dyons in p-p collisions
- Enabled by recent theoretical advances, MoEDAL performed the first search for magnetic monopoles produced in Pb-Pb collisions via the Schwinger mechanism at the LHC
  - 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

Bonus: Expected rate of trapped monopoles

[Nature 602 (2022) 7895, 63-67]



Bonus: MoEDAL in the VELO cavern



Bonus: What's next for MoEDAL

- More work ahead!
  - LHC Run-3
  - Inclusion of the NTD data
  - Extension of MoEDAL detectors to search for long-lived and millicharged particles (MAPP and MALL)
  - Search for high-charge (> $5g_D$) monopoles in the CMS beampipe
  - Expected improvement in theoretical calculations

Bonus: CMS Run-1 beampipe

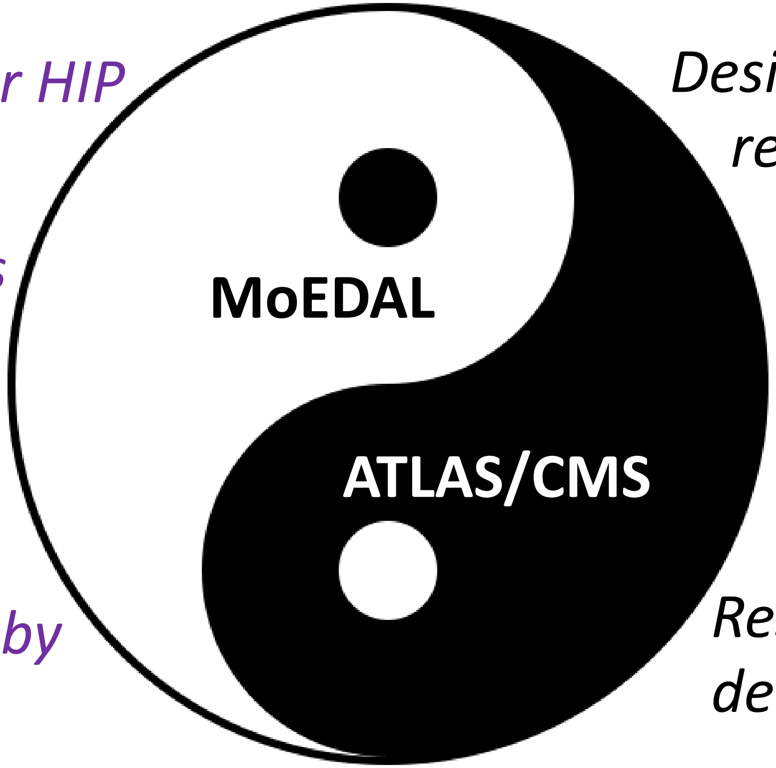
Bonus: Complementarity

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

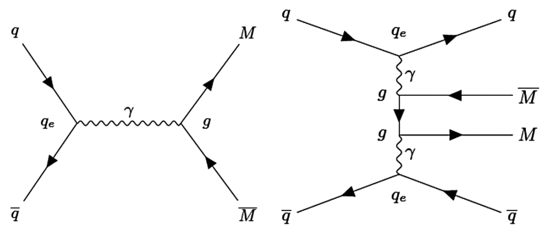
Sophisticated triggers

Can infer magnetic charge from tracking and dE/dx

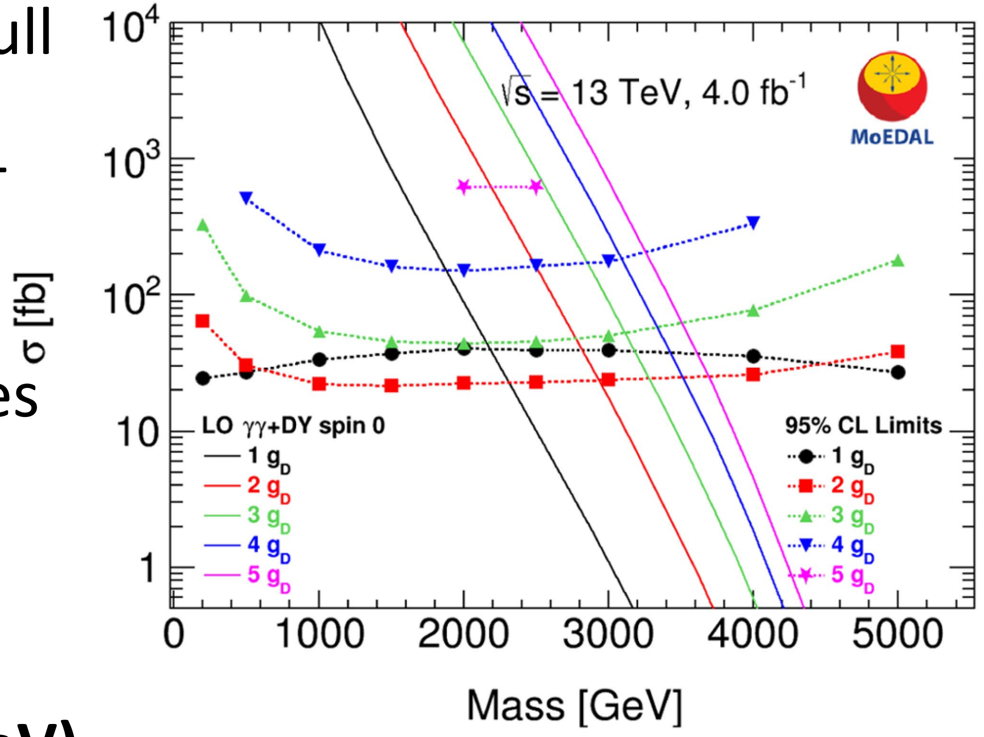
Response estimated from detailed Monte Carlo

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

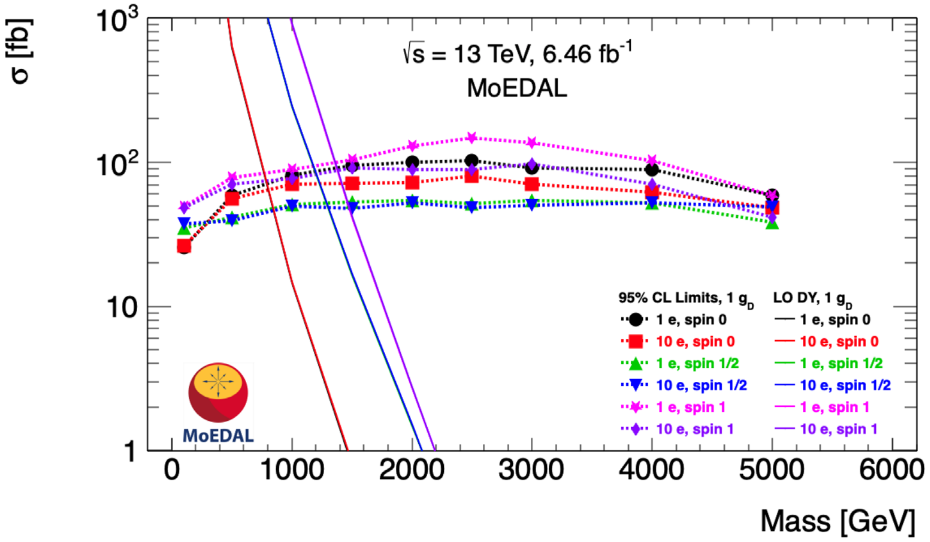
Bonus: Recent Results

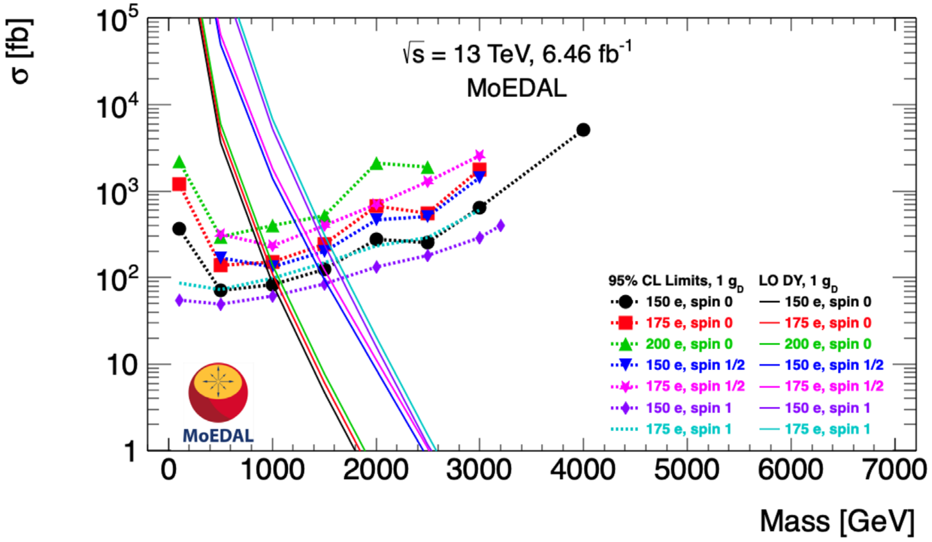


- "Magnetic monopole search with the full MoEDAL trapping detector in 13 TeV pp collisions interpreted in photon-fusion and Drell-Yan production"
  - *Phys. Rev. Lett.* ***123****, 021802 (2019)*
- For the first time at the LHC, monopoles were searched for via photon-fusion mechanism (in addition of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



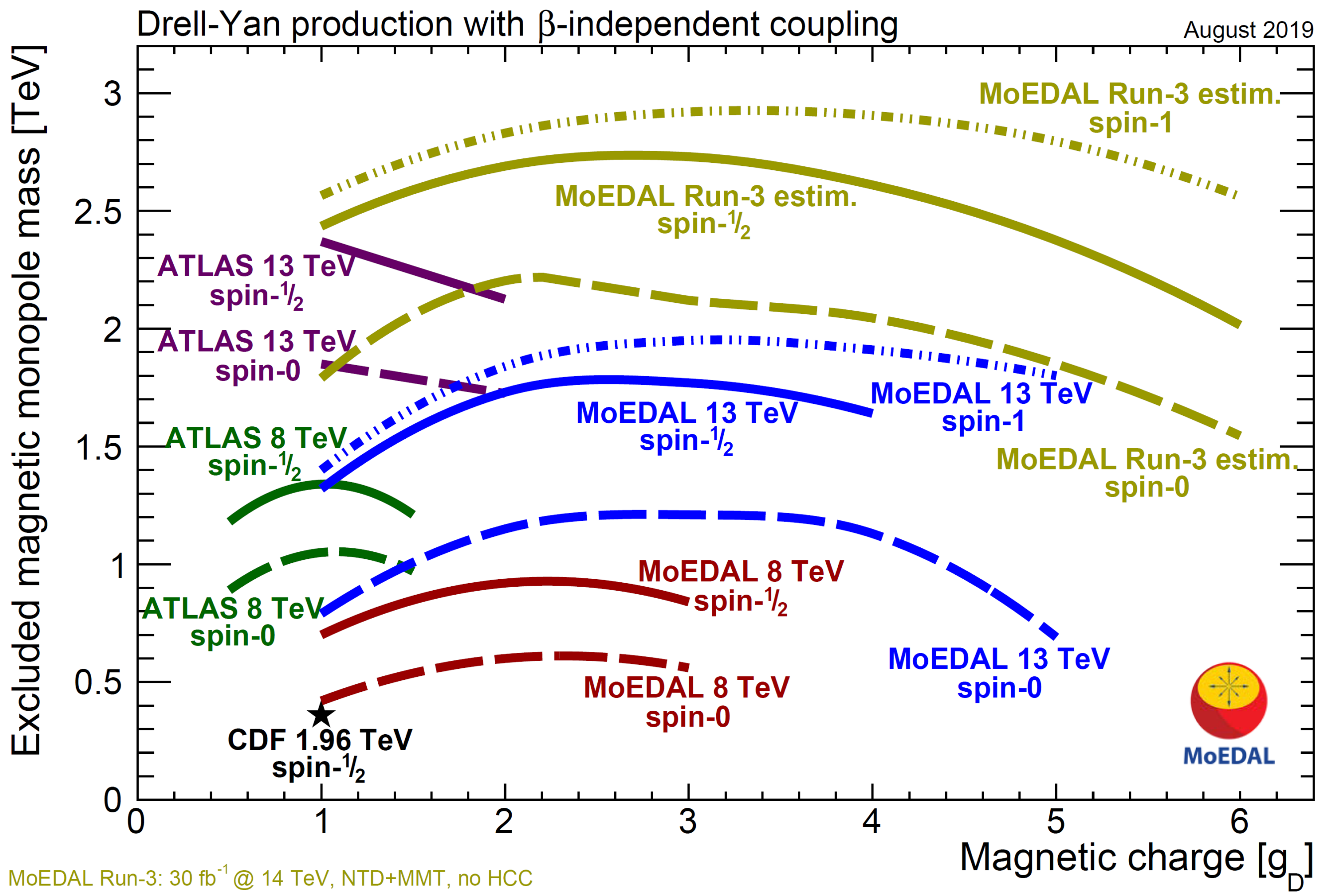
Bonus: Recent Results

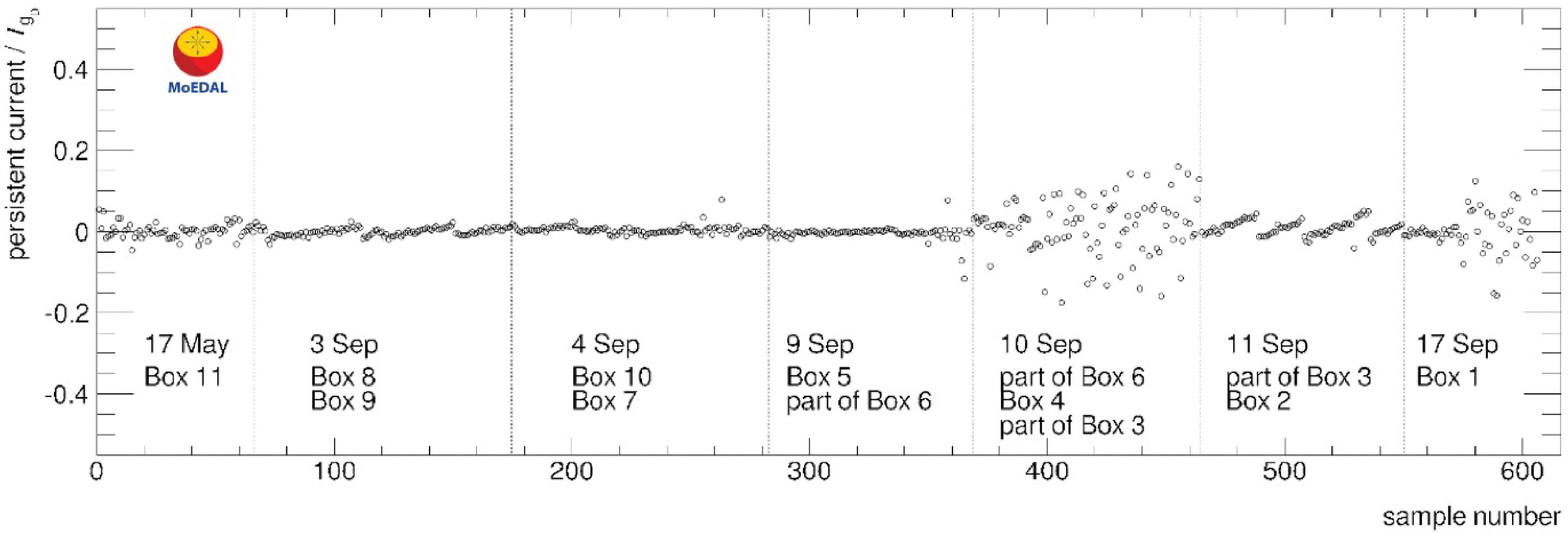




- "First search for dyons with the full MoEDAL trapping detector in 13 TeV pp collisions"
  - *Phys. Rev. Lett.* ***126****, 071801 (2021)*
  - **Mass limits 0.79–1.91 TeV on dyons with up to $5g_D$ magnetic and $1e - 200e$ electric charges**

Bonus: State of the field and Run-3 projection




persistent current / I_{g_D}
MoEDAL
0.4
0.2
0
-0.2
-0.4
17 May
Box 11
3 Sep
Box 8
Box 9
4 Sep
Box 10
Box 7
9 Sep
Box 5
part of Box 6
10 Sep
part of Box 6
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11 Sep
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600
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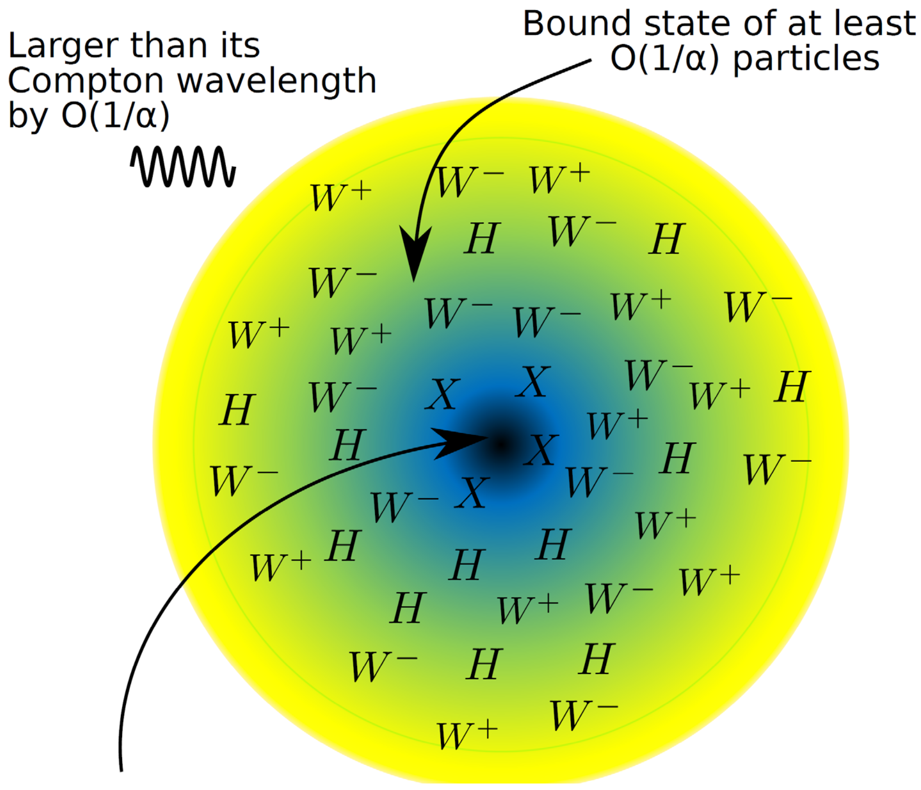
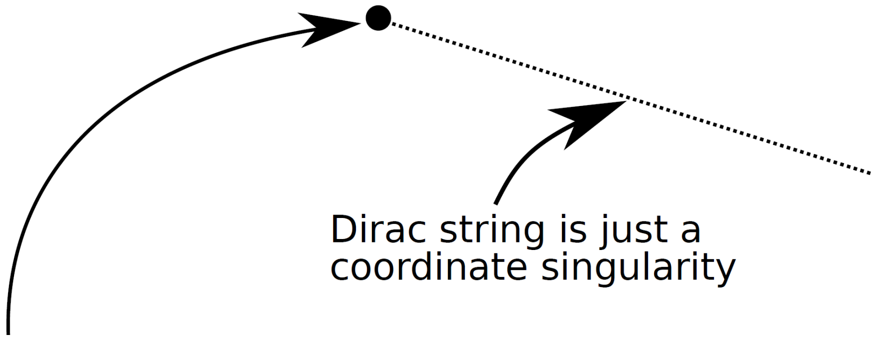


Consistent QFT of
elementary monopoles
exists

Any mass is possible



Composite

Point-like

Credit: Oliver Gould