Searching for Magnetic Monopoles with the MoEDAL Experiment

Albert De Roeck
CERN, Geneva, Switzerland

SUSY 2016 Melbourne
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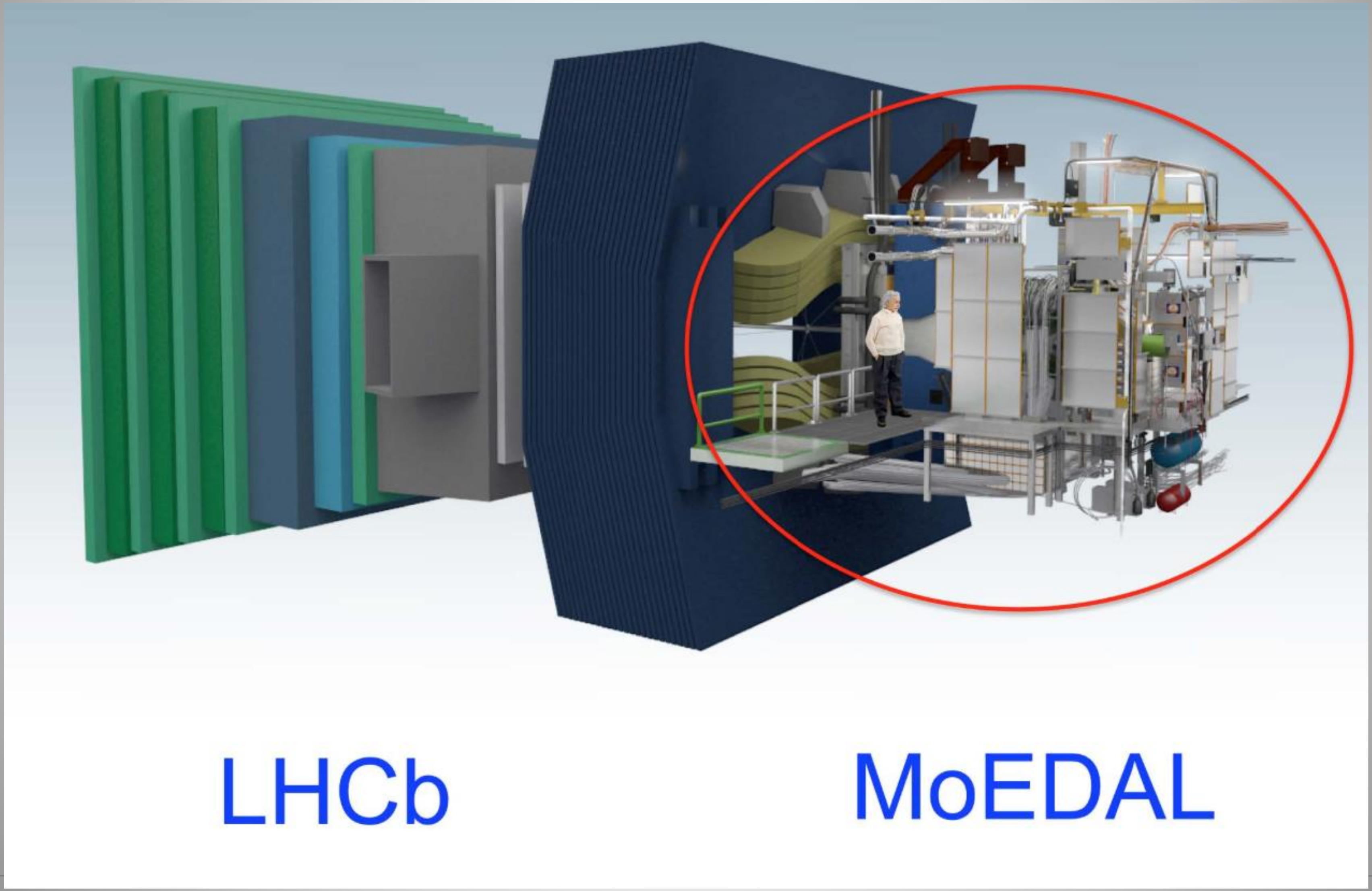
The MoEDAL Experiment



The MoEDAL Experiment

- MoEDAL is an experiment for the search of heavy stable ionizing particles at LHC energies.
- The MoEDAL experiment, the 7th LHC experiment, was officially approved by the CERN Research Board on March 3rd 2010
- MoEDAL shares the 8th LHC IP with the LHCb experiment
- MoEDAL is an array of passive Nuclear Track-Etch Detectors & Trapping Detectors, with a MediPix chip based online radiation monitor system
- The complete MoEDAL experiment has started data taking at the LHC in spring of 2015.
- A 20% prototype of the full Trapping Detector was installed in the second half of 2012 and collected the first data. The results of these data are presented today

The Collaboration

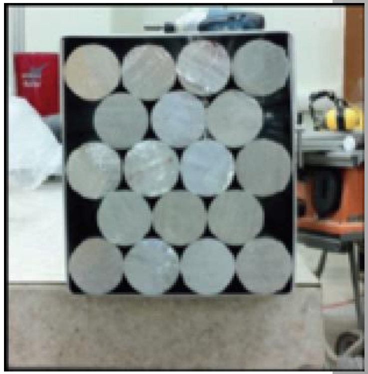
- *Now 66 physicists from 16 countries and 26 institutions:*
  - *U. Alberta, UBC, INFN Bologna, U. Bologna,CAAG (Algeria), Algeria, U. Cincinatti, Concordia U., Gangneung-Wonju Nat. U., U. Geneva, U. Helsinki, ICTP Trieste, IEAP/CTU Prague, IFIC Valencia, Imperial College London, INP/PAS Cracow, ISS Bucharest, King's College London, Konkuk U., MiSIS U. Moscow, Muenster U., National Inst. Tec. (india),Northeastern U., Simon Langton School UK, Stanford U (Associate), Tuft's.*

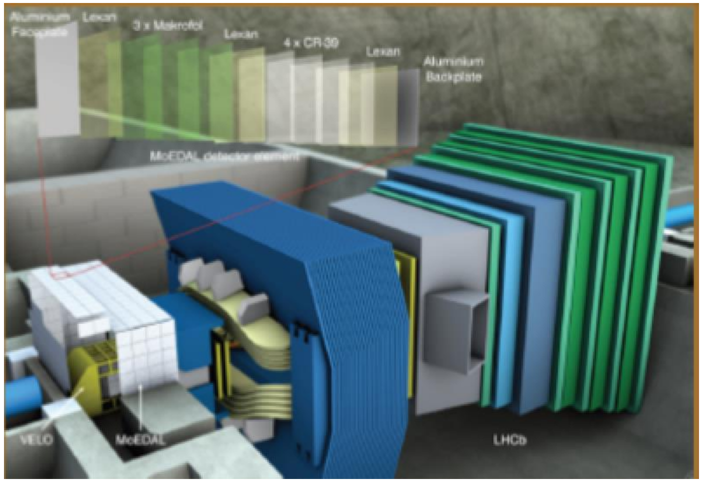
The MoEDAL Experiment

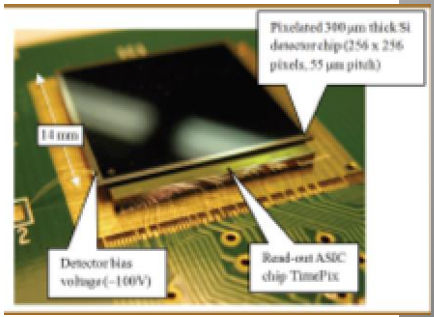
-> Three subdetector systems

- Passive Nuclear Track-Etch Detectors (NTDs)
  - 18m^2 of CR39 and Makrofol (for very high ionization)
  - Detection threshold is “charge/β > 5”
- Passive Trapping Detectors (MMTs)
  - 800 kg of aluminium bars
- MediPix chip based online radiation monitor system

The NTD and MMT detectors have been exchanged in December ‘15. These removed detector are being analysed







Magnetic Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac '31)

$$\nabla . \mathrm{E} = 4\pi \rho_e$$

$$\nabla . \mathrm{B} = 4\pi \rho_m$$

$$-\nabla \times \mathrm{E} = \frac{1}{c}\frac{\partial \mathrm{B}}{\partial t} + \frac{4\pi}{c}\mathrm{j_m}$$

$$\nabla \times \mathrm{B} = \frac{1}{c}\frac{\partial \mathrm{E}}{\partial t} + \frac{4\pi}{c}\mathrm{j_e}$$

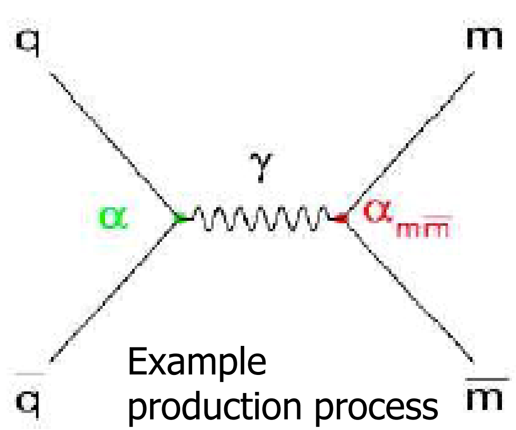
$$\mathrm{F} = q_e\left(\mathrm{E} + \frac{\mathrm{v}}{c} \times \mathrm{B}\right) + q_m\left(\mathrm{B} - \frac{\mathrm{v}}{c} \times \mathrm{E}\right)$$

$$g = \frac{q_m}{e} = \frac{n}{2\alpha_\mathrm{e}} = n \cdot g_\mathrm{D} \approx n \cdot 68.5$$

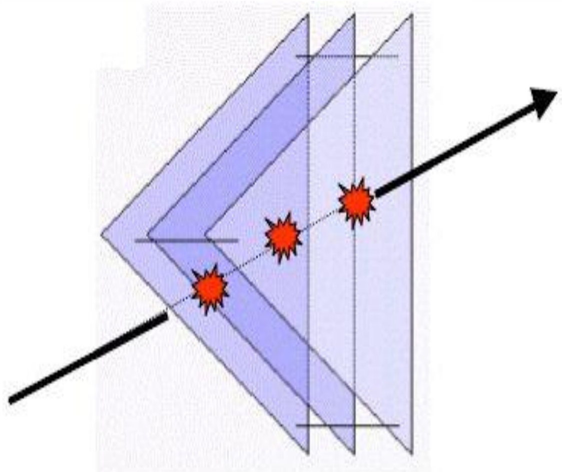
g_D is the Dirac unit magnetic charge

- Symmetrizes Maxwell equations!
- Dirac: Charge quantization consequence of angular momentum quantization in the presence of monopole
- 't Hooft, Polyakov: GUT monopoles
- Cho-Maison: Electroweak monopoles in the TeV range. Recent discussion: Elis et al.:arXiv:1602.01745

Collider signature: pair production of very highly ionizing particles!

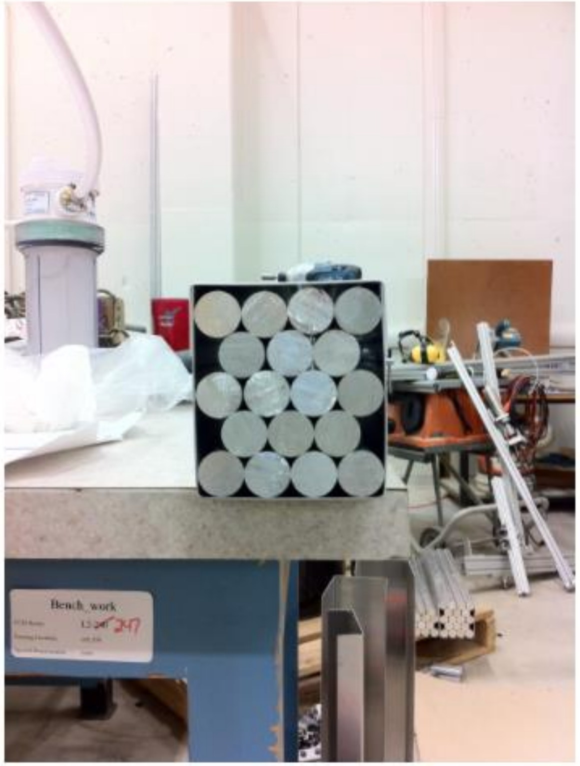


Example production process



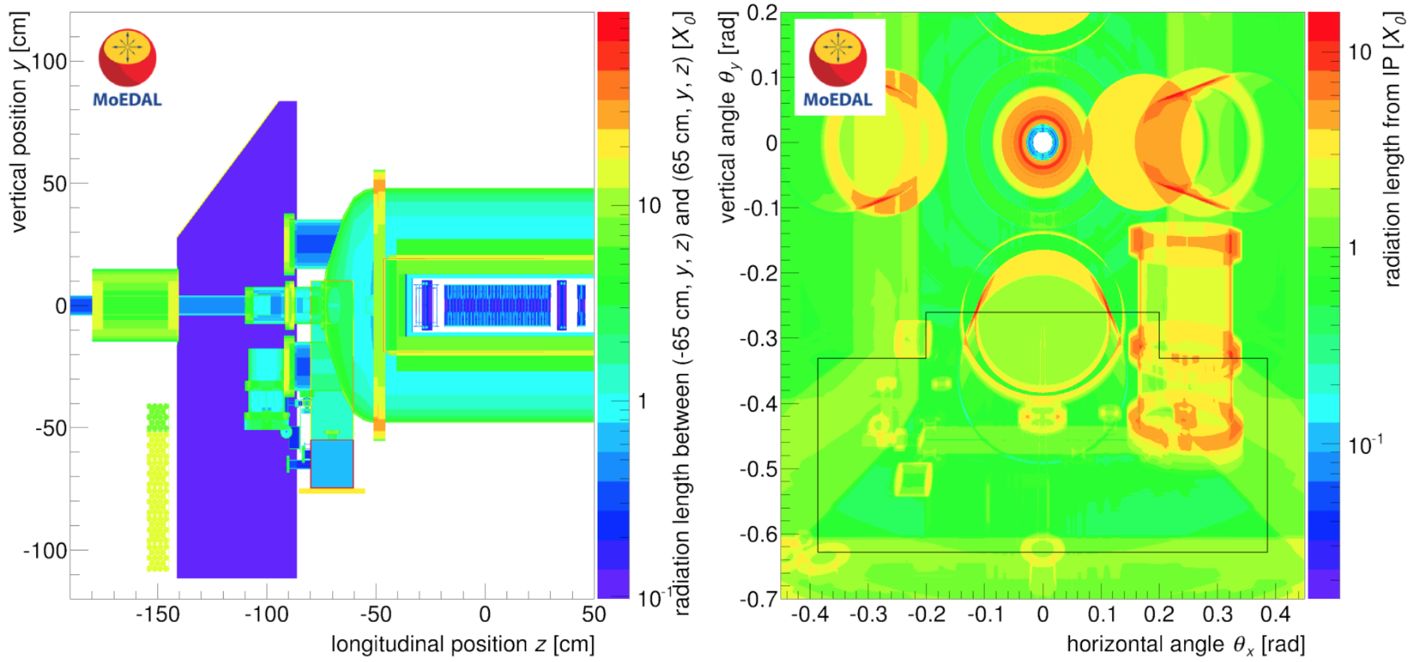
Monopoles will 'burn' through the plastic sheets of the experiment or get trapped in the dense material of the trapping detector

Results Based on the 2012 Prototype



- Magnetic Monopole Trapper prototype deployed in September 2012 and exposed to 0.75 fb^{-1} of 8 TeV pp collisions
- 160 kg Magnetic Monopole Trapper made of 198 aluminium rods of 2.5 cm diameter and 60 cm length

Geometry Description in Geant4



- Good knowledge of material between the IP and detector essential to determine monopole stopping position. Dominating systematics!
- Implemented into XML file already containing the LHCb detector geometry.
- Then used by Geant4 within the LHCb software framework for simulating monopole propagation in the material.

Magnetometer Measurements

Laboratory of Natural Magnetism, ETH Zurich

Magnetically shielded room

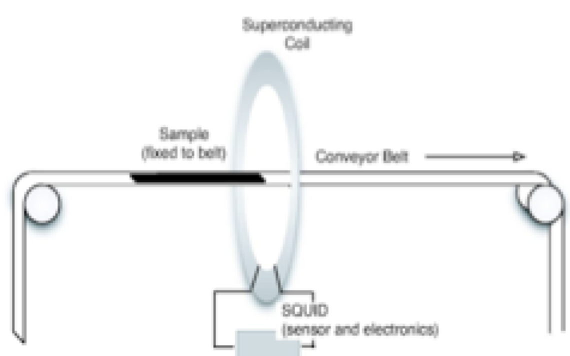
DC-SQUID magnetometer

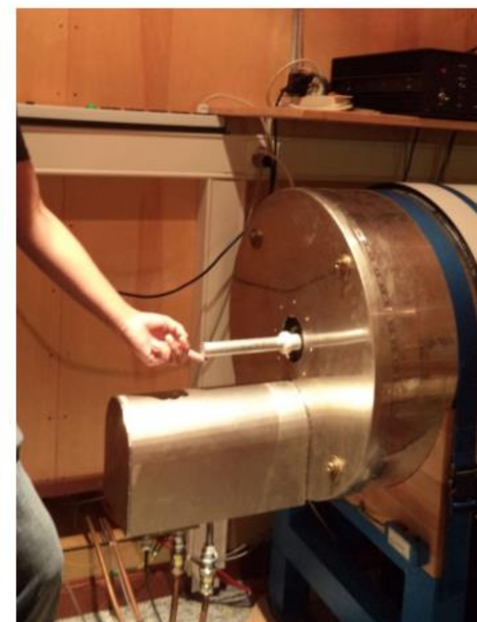
->Detection Method: Measure a persistent current induced in the superconducting coil of a sensitive SQUID magnetometer

Magnetometer scans

- Optimum length 20 cm
- 11 boxes (606 samples) in 7 days
- 852 independent runs (including calibration, backgrounds, and multiple measurements of candidates)

A DC-SQUID rock magnetometer (2G Enterprises model 755)

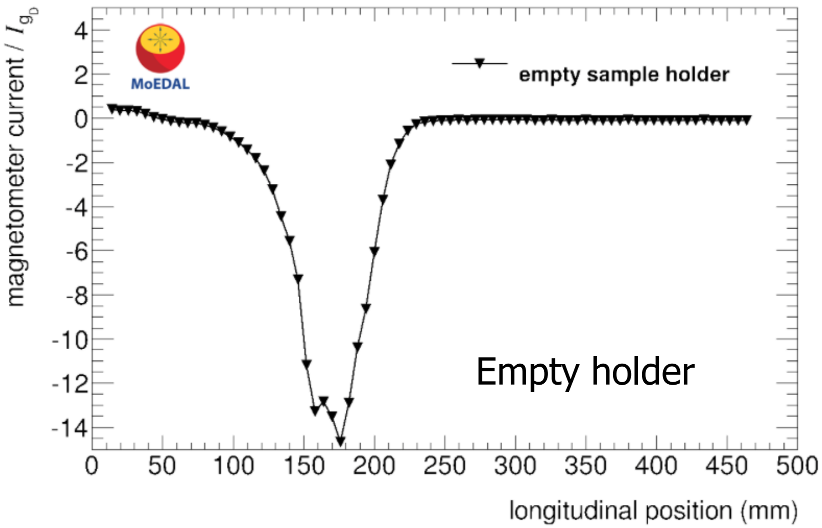


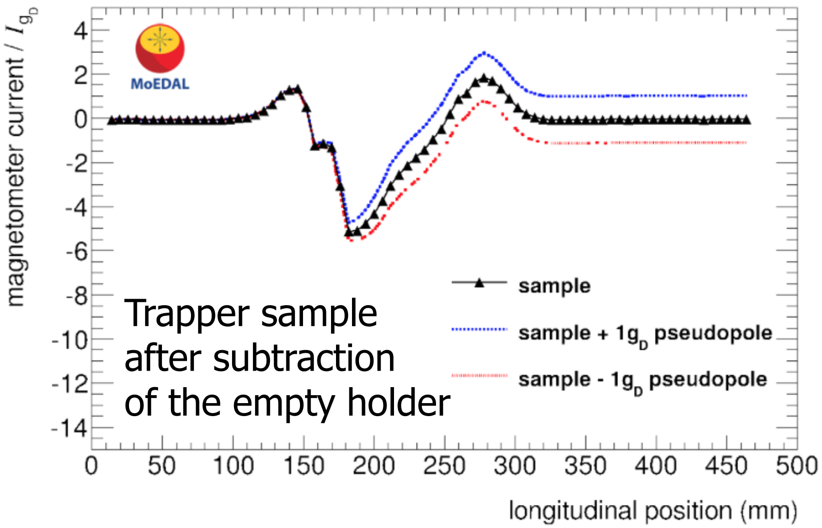


Magnetometer Measurement Procedure

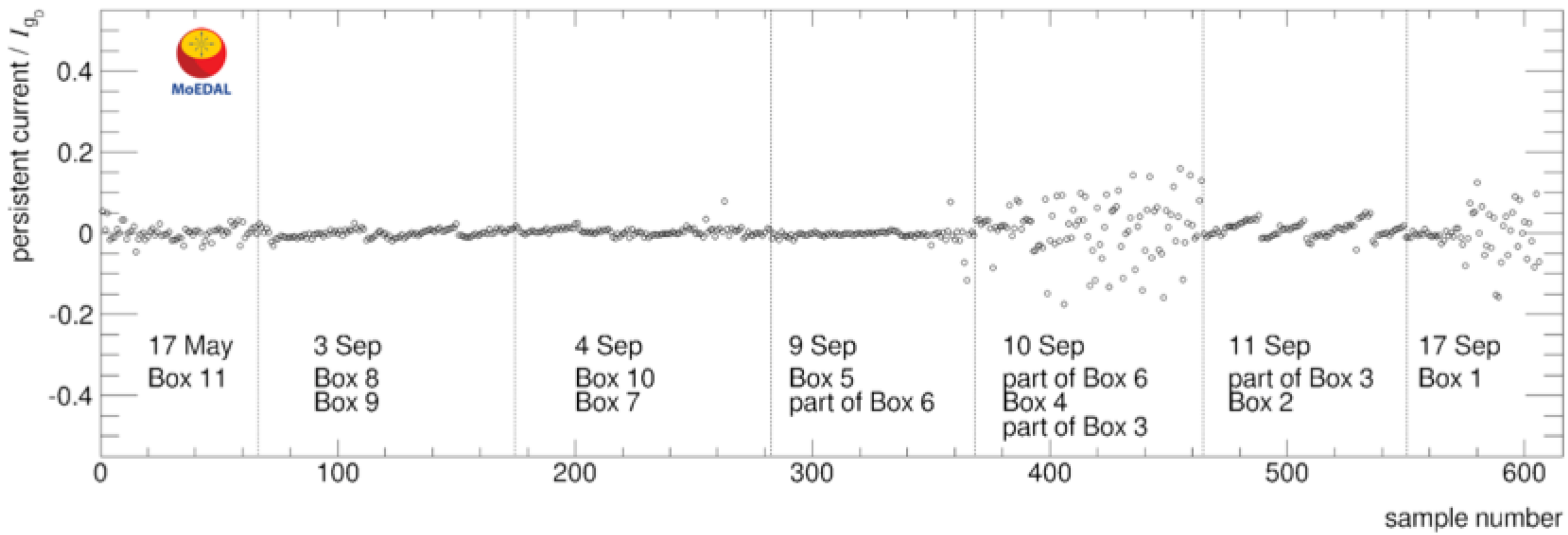
- Output measured before, during and after the passage of the sample through the sensitive coil
- Calibration with a convolution method applied to a dipole sample and cross checked with thin long thin dipoles mimicking a monopole of well known charge.
- Subtract the empty holder result from the measurement.
- The difference is the persistent current. If it differs from zero we have a monopole signal candidate!!

Measurement of one 20 cm sample in 76 step through the SQUID

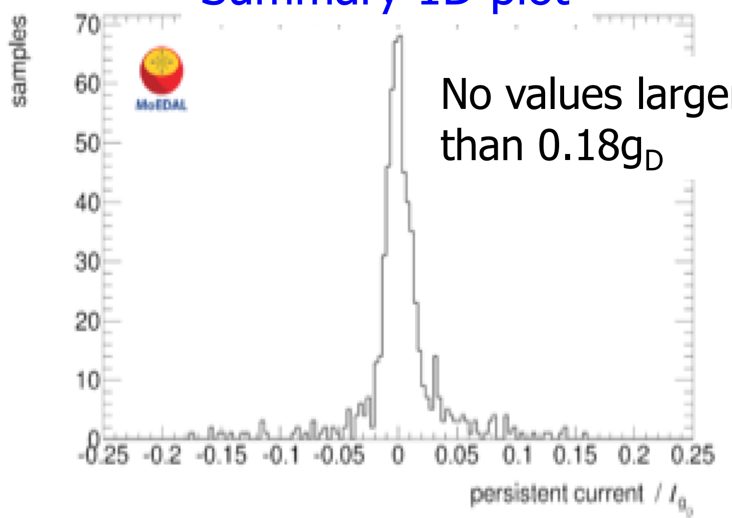




Measure of Magnetic Charges: Results



Summary 1D plot

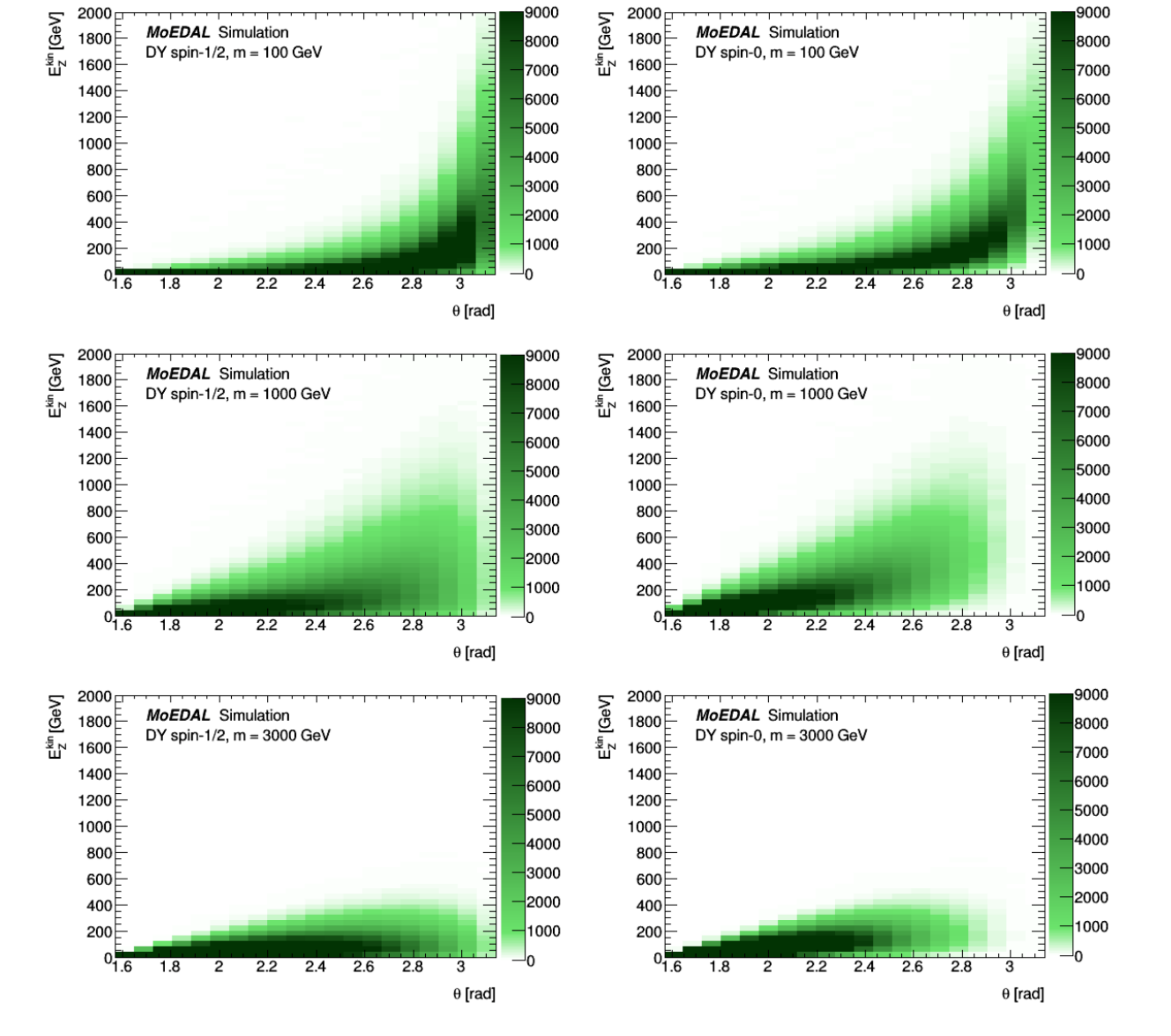


No values larger than $0.18g_D$

- All 606 sample measurements
- Some device instabilities in the last part
- Exclude a trapped magnetic charge with $|g| > 0.5\ g_D$ at the 99.75% confidence level, in the full sample

Monopole Event Simulation

Drell–Yan Process



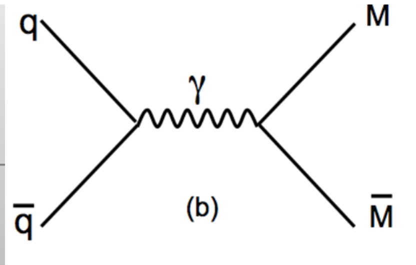
Two acceptance studies:

Single monopoles with flat θ, φ and Ekin distributions

Pair production: Drell-Yan model with spin ½ and spin-0 monopoles give different kinematics (with MadGraph)

Energy loss simulated in Geant4 & arXiv:1606.01220 (see also backup)

Note: non-perturbative!

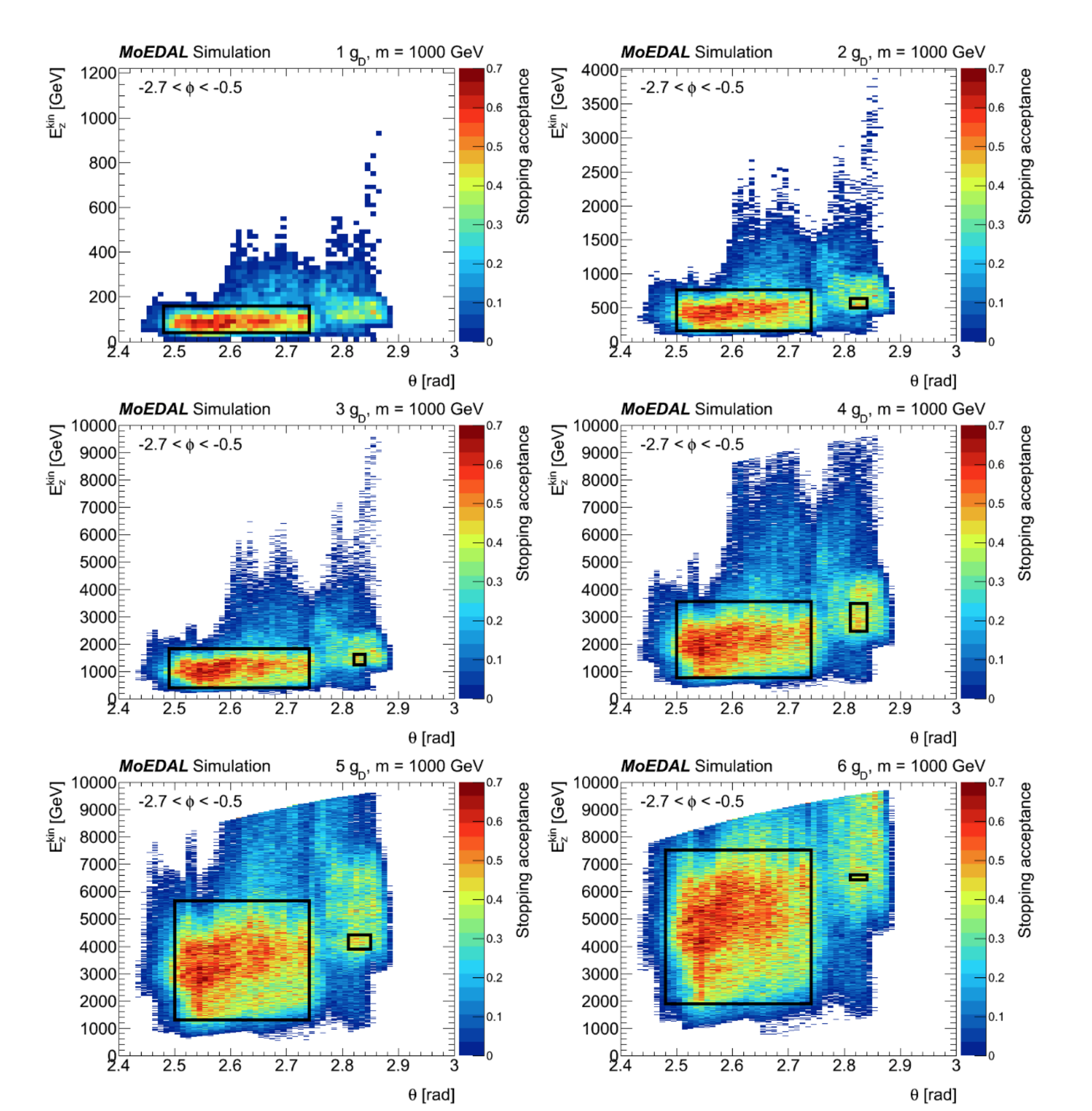


Acceptance for spin ½ and spin 0

m [GeV]	$\lvert g\rvert = 1.0g_{\mathrm{D}}$	$\lvert g\rvert = 2.0g_{\mathrm{D}}$	$\lvert g\rvert = 3.0g_{\mathrm{D}}$	$\lvert g\rvert = 4.0g_{\mathrm{D}}$
spin-1/2				
100	0.019±0.003	0.002±0.002	—	—
500	0.017±0.001	0.021±0.005	0.005±0.003	—
1000	0.014±0.001	0.022±0.004	0.008±0.004	0.002±0.001
2000	0.012±0.001	0.022±0.003	0.008±0.004	0.001±0.001
3000	0.016±0.001	0.013±0.004	0.002±0.002	—
3500	0.020±0.001	0.004±0.003	—	—
spin-0				
100	0.028±0.002	0.007±0.004	—	—
500	0.0082±0.0010	0.027±0.004	0.010±0.005	0.002±0.002
1000	0.0038±0.0007	0.022±0.002	0.011±0.004	0.003±0.002
2000	0.0020±0.0004	0.014±0.001	0.008±0.003	0.002±0.002
3000	0.0032±0.0007	0.008±0.002	0.002±0.002	—
3500	0.0069±0.0007	0.004±0.002	—	—

Trapping acceptance Assuming (LO) Drell-Yan production kinematics

Acceptance for Single Monopoles



Studied for a magnetic charge of up to $6g_D$

First Analysis & Paper…

arXiv.org > hep-ex > arXiv:1604.06645

Search or Articl

April 2016

High Energy Physics – Experiment

Search for magnetic monopoles with the MoEDAL prototype trapping detector in 8 TeV proton–proton collisions at the LHC

MoEDAL Collaboration: B. Acharya, J. Alexandre, K. Bendtz, P. Benes, J. Bernabéu, M. Campbell, S. Cecchini, J. Chwastowski, A. Chatterjee, M. de Montigny, D. Derendarz, A. De Roeck, J. R. Ellis, M. Fairbairn, D. Felea, M. Frank, D. Frekers, C. Garcia, G. Giacomelli, D. Haşegan, M. Kalliokoski, A. Katre, D.-W. Kim, M. G. L. King, K. Kinoshita, D. H. Lacarrère, S. C. Lee, C. Leroy, A. Lionti, A. Margiotta, N. Mauri, N. E. Mavromatos, P. Mermod, D. Milstead, V. A. Mitsou, R. Orava, B. Parker, L. Pasqualini, L. Patrizii, G. E. Păvălaş, J. L. Pinfold, M. Platkevič, V. Popa, M. Pozzato, S. Pospisil, A. Rajantie, Z. Sahnoun, M. Sakellariadou, S. Sarkar, G. Semenoff, G. Sirri, K. Sliwa, R. Soluk, M. Spurio, Y. N. Srivastava, R. Staszewski, M. Suk, J. Swain, et al. (10 additional authors not shown)

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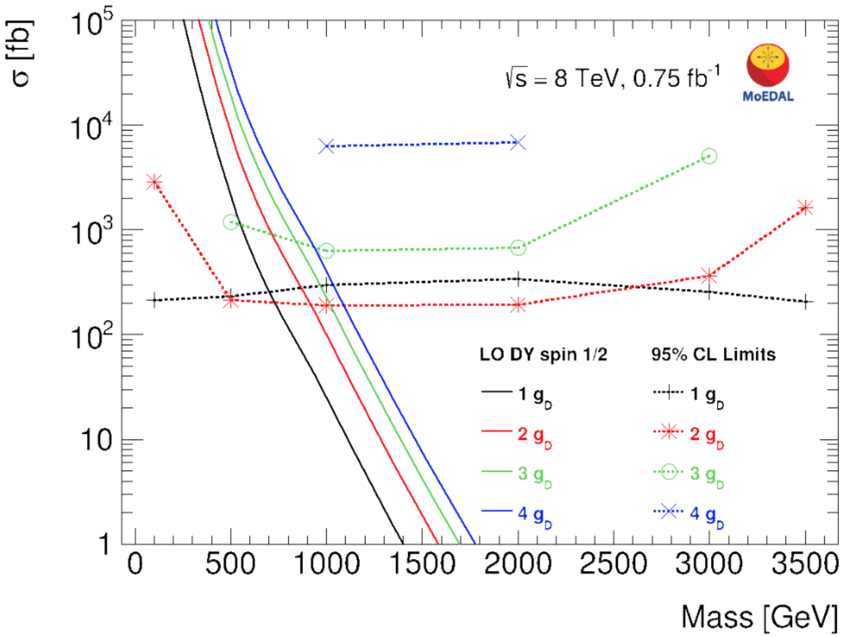
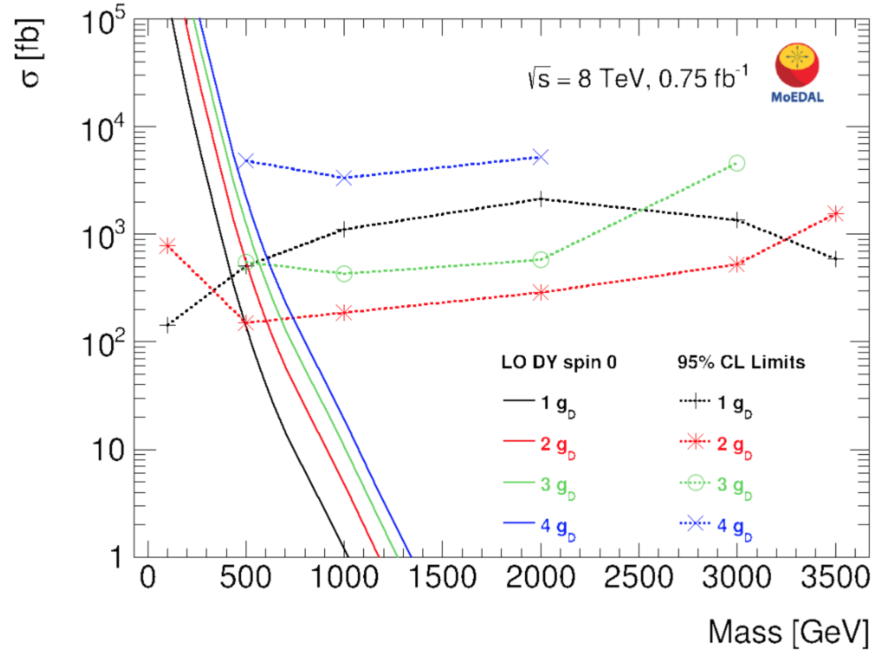
The MoEDAL experiment is designed to search for magnetic monopoles and other highly-ionising particles produced in high-energy collisions at the LHC. The largely passive MoEDAL detector, deployed at Interaction Point 8 on the LHC ring, relies on two dedicated direct detection techniques. The first technique is based on stacks of nuclear-track detectors with surface area $\sim$18 m^2, sensitive to particle ionisation exceeding a high threshold. These detectors are analysed offline by optical scanning microscopes. The second technique is based on the trapping of charged particles in an array of roughly 800 kg of aluminium samples. These samples are monitored offline for the presence of trapped magnetic charge at a remote superconducting magnetometer facility. We present here the results of a search for magnetic monopoles using a 160 kg prototype MoEDAL trapping detector exposed to 8 TeV proton-proton collisions at the LHC, for an integrated luminosity of 0.75 fb^{-1}. No magnetic charge exceeding $0.5g_{\rm D}$ (where $g_{\rm D}$ is the Dirac magnetic charge) is measured in any of the exposed samples, allowing limits to be placed on monopole production in the mass range 100 GeV $\leq m \leq$ 3500 GeV. Model-independent cross-section limits are presented in fiducial regions of monopole energy and direction for $1g_{\rm D} \leq |g| \leq 6g_{\rm D}$, and model-dependent cross-section limits are obtained for Drell-Yan pair production of spin-1/2 and spin-0 monopoles for $1g_{\rm D} \leq |g| \leq 4g_{\rm D}$. Under the assumption of Drell-Yan cross sections, mass limits are derived for $|g| = 2g_{\rm D}$ and $|g| = 3g_{\rm D}$ for the first time at the LHC, surpassing the results from previous collider experiments.

Limits for Different Monopole Charges

Search results versus the monopole mass





- World best limits for $|g| > g_D$ (previously ~400 GeV at Tevatron)

DY Lower Mass Limits [GeV]	$\lvert g\rvert = g_D$	$\lvert g\rvert = 2g_D$	$\lvert g\rvert = 3g_D$
spin-1/2	700	920	840
spin-0	420	600	560

arXiv:1509.08059

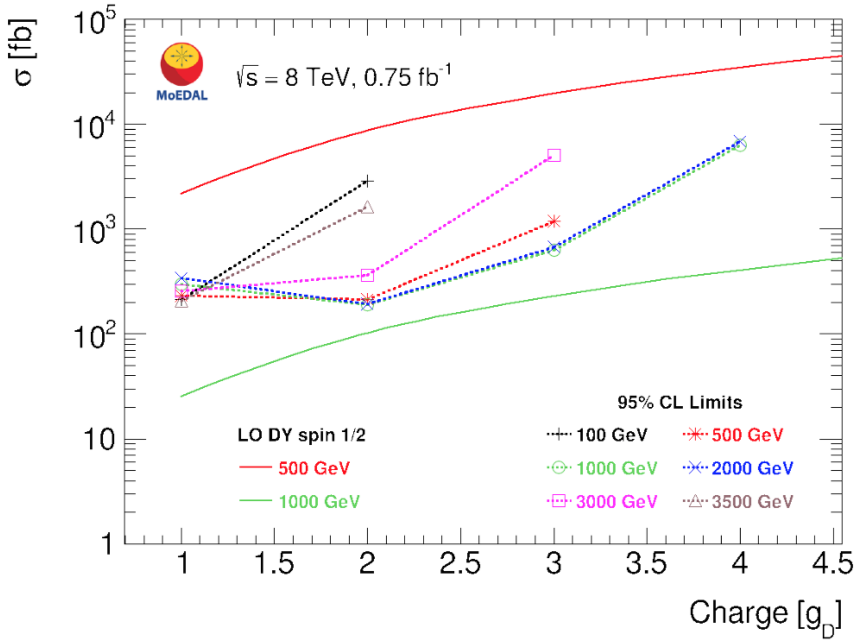
ATLAS 8 TeV

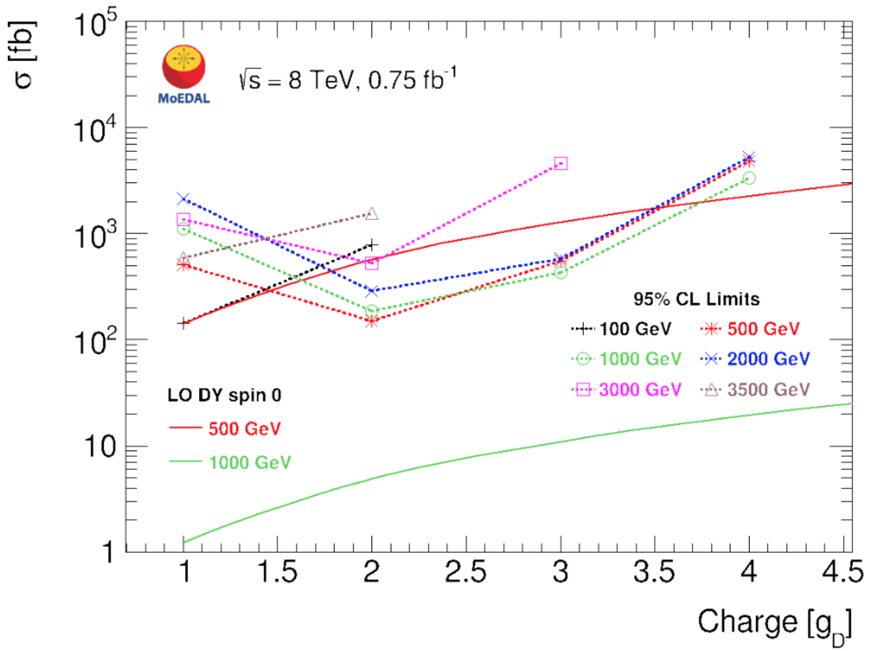
$\lvert g\rvert = g_D$
1340
1050

- Limits on masses in the range of 100 GeV < m < 3500 GeV
- In particular sensitive to high magnetic charges (new at the LHC!)

Limits for Different Monopole Charges

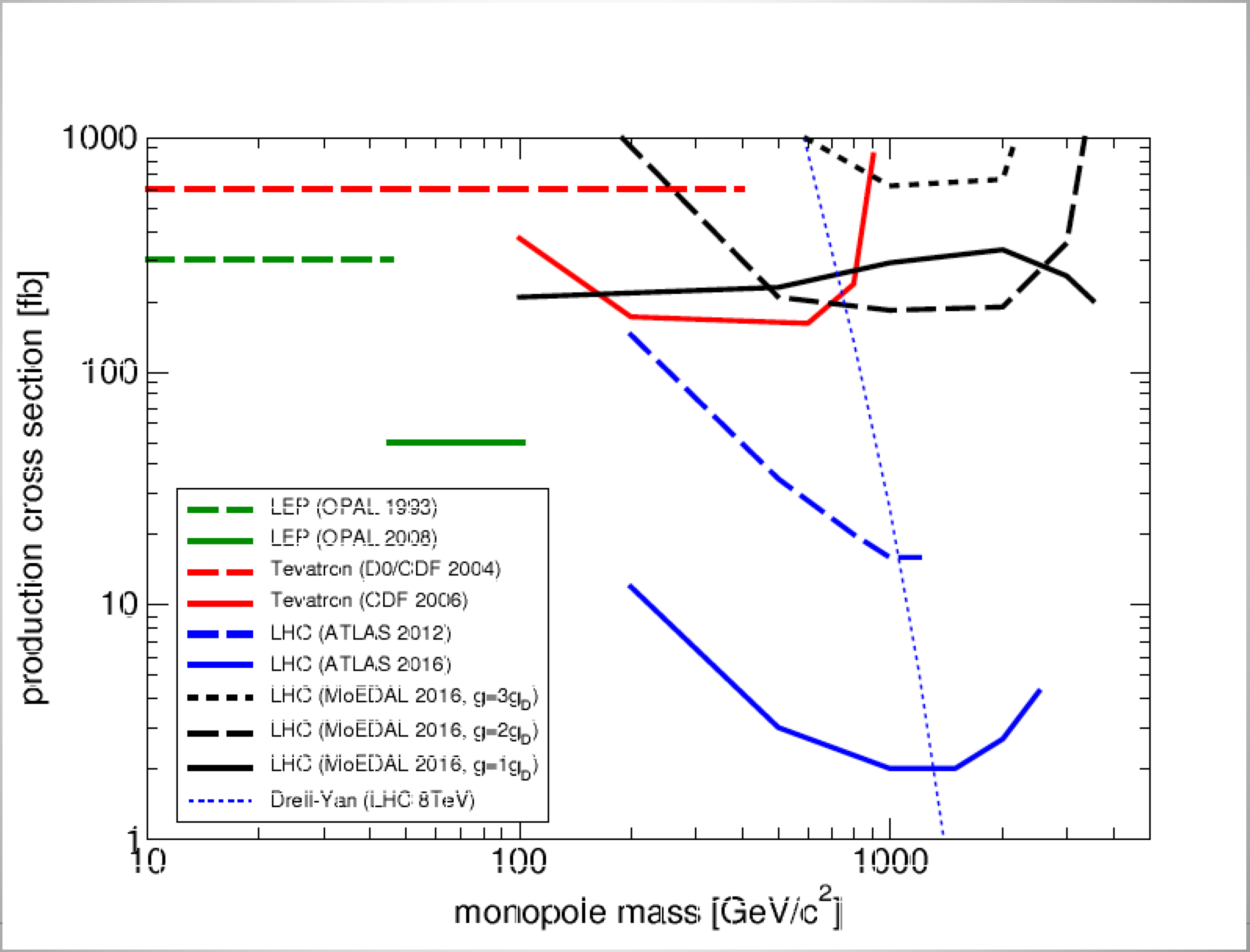
Search results versus the monopole charge





DY cross section are calculated at leading order but note that perturbative calculations are not reliable due to large coupling

Comparison with other Measurements



MoEDAL in Run-2

MoEDAL in 2015/2016

NDTs on top of VELO, close to IP

TimePix chips

3 arrays trapping detectors

Thin “curtain” within LHCb acceptance

- Full arrays exposed to 13 TeV *pp* collisions

Summary

- The first results from MoEDAL, a dedicated LHC experiment for the search of heavy stable ionizing particles have been released, using a 160 kg prototype Magnetic Monopole Trapper, and based on 0.75 fb^{-1} of data at 8 TeV
- The samples have been analysed by a SQUID magnetometer
- No monopole candidates with a magnetic charge of ≥ $0.5g_D$ were found in the full trapping sample.
- Under the assumption of a DY production at LO, mass limits are obtained for magnetic charge of up to $3g_D$
- Model independent results put a 95% CL upper limit of 10 fb for magnetic charges up to $6g_D$
- 2015 data (trapper and plastic foils) being analysed.
- Detector is equipped for the 2016 run and collecting data since the start of the run.

Heavy Ionizing Particles

- *Electric charge - ionization increases with increasing charge & falling velocity β (β=v/c) – use z/β as an indicator of ionization*

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

- *Magnetic charge - ionization increases with magnetic charge and decreases with velocity β – a unique signature*

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

  - *The velocity dependence of the Lorentz force cancels $1/\beta^2$ term*

- *The ionization of a relativistic monopole is $(ng)^2$ times that of a relativistic proton i.e $4700n^2$!! (n=1,2,3...)*