First search for magnetic monopoles from the MoEDAL experiment at LHC

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IFIC – CSIC / Valencia Univ.

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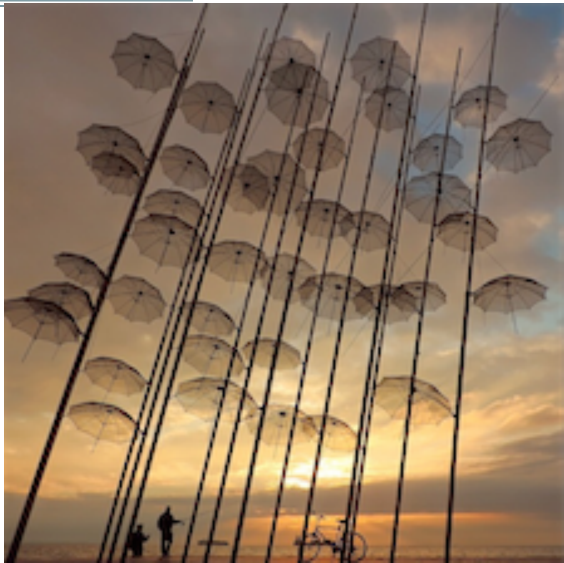

MoEDAL at LHC

Monopole & Exotics Detector At LHC

International collaboration ~65 physicists from 20 participating institutions

UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
CERN
UNIVERSITY OF CINCINNATI
CONCORDIA UNIVERSITY
GANGNEUNG-WONJU NATIONAL UNIVERSITY
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TECHNICAL UNIVERSITY IN PRAGUE
INSTITUTE FOR SPACE SCIENCES, ROMANIA
STAR INSTITUTE, SIMON LANGTON SCHOOL
TUFT'S UNIVERSITY
IFIC VALENCIA

Physics goals for MoEDAL

Key feature: **high ionisation**

$$\frac{\text{charge}}{\text{velocity: } \beta = v/c} = z/\beta$$

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

Electric charge

Bethe-Bloch formula

High ionisation possible when:

- multiple electric charge (H^{++}, Q-balls, etc.) = n × e
- very low velocity & electric charge, e.g. Stable Massive Particles (SMPs)
- magnetic charge (monopoles, dyons) = ng_D = n × 68.5 × e
  - a singly charged relativistic monopole has ionisation ~4700 times MIP!!
- any combination of the above

MoEDAL detectors have a threshold of **z/β ~ 5**

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

Magnetic charge

Ahlen formula

Particles must be *massive*, *long-lived* & *highly ionising* to be detected at *MoEDAL*

Complementarity of MoEDAL & other LHC exps

ATLAS+CMS

- The main LHC detectors are optimised for the detection of singly (electrically) charged (or neutral) particles ($Z/\beta \sim 1$) moving near to the speed of light ($\beta > 0.5$)
- Typically a largish statistical sample is needed to establish a signal

MoEDAL

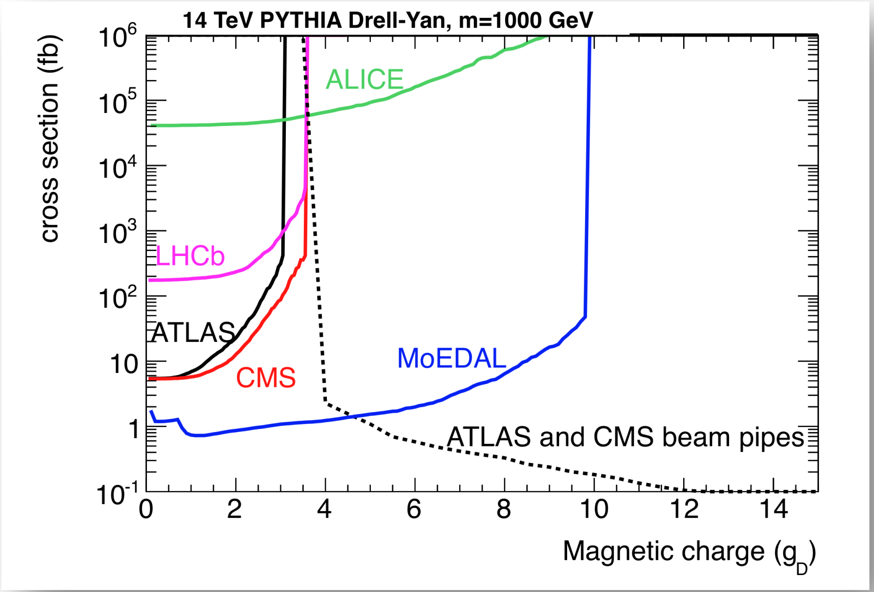
- MoEDAL is designed to detect charged particles, with effective or actual $Z/\beta > 5$
- As it has no trigger/electronics slowly moving ($\beta < \sim 0.5$) particles are no problem
- One candidate event should be enough to establish a signal (no SM backgrounds)

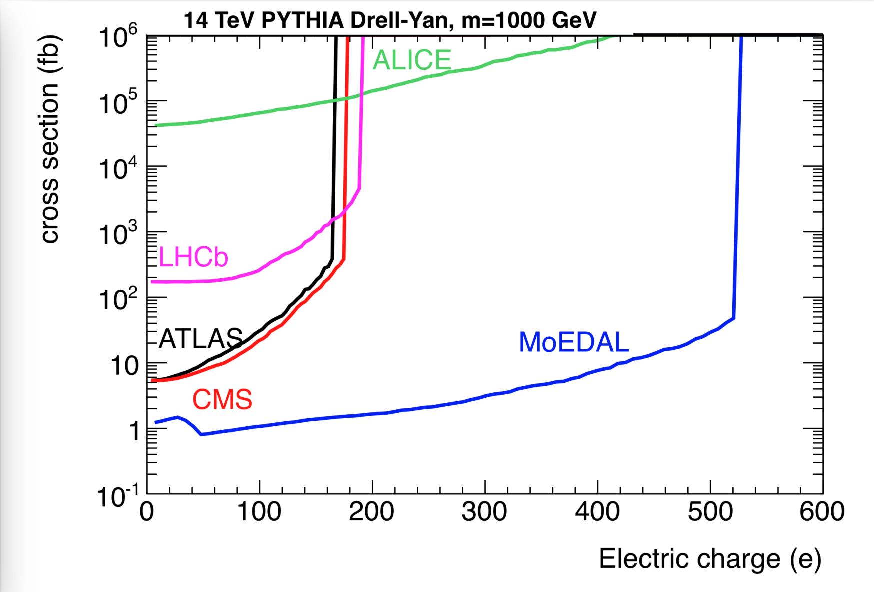
MoEDAL strengthens & expands the physics reach of LHC

MoEDAL sensitivity

Cross-section limits for magnetic and electric charge assuming that:

- ~ one MoEDAL event is required for discovery and ~100 events in the other LHC detectors
- integrated luminosities correspond to about two years of 14 TeV run

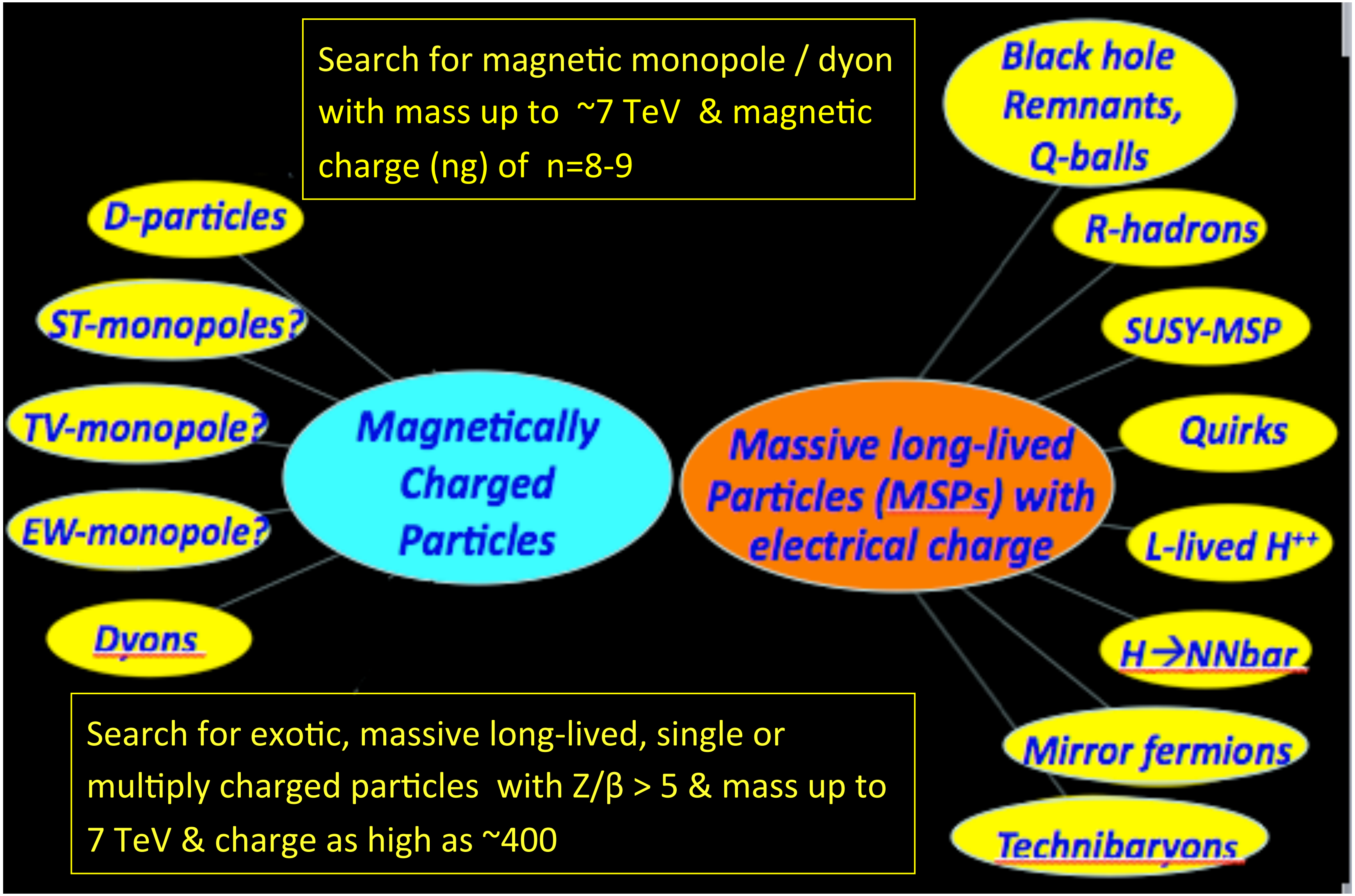




De Roeck, Katre, Mermod, Milstead, Sloan, EPJC72 (2012) 1985 [arXiv:1112.2999]

MoEDAL offers robustness against timing and well-estimated signal efficiency

The MoEDAL Physics Program



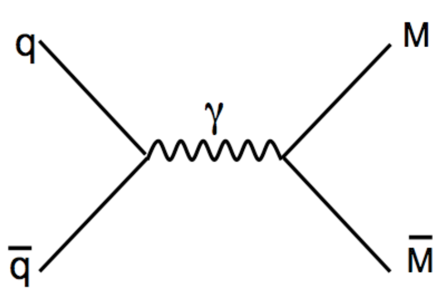
Magnetic monopoles

- Motivation
  - symmetrisation of Maxwell's eqs.
  - electric charge quantisation
- Properties
  - magnetic charge = ng = n×68.5e
    coupling constant = g/ħc ~34
  - spin and mass not predicted

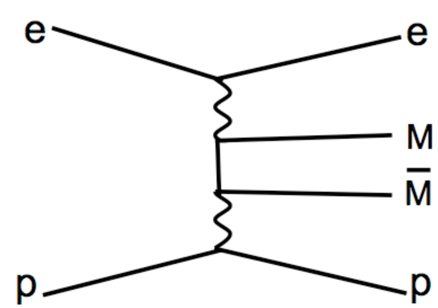
Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla} \cdot \vec{E} = 4\pi \rho_e$	$\vec{\nabla} \cdot \vec{E} = 4\pi \rho_e$
Gauss' law for magnetism:	$\vec{\nabla} \cdot \vec{B} = 0$	$\vec{\nabla} \cdot \vec{B} = 4\pi \rho_m$
Faraday's law of induction:	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi \vec{J}_m$
Ampère's law (with Maxwell's extension):	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$

HIGHLY IONISING

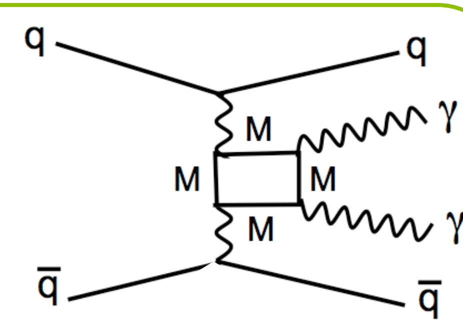
Production mechanisms in colliders



Drell Yan mechanism



Photon fusion



Box diagram

MoEDAL improves reach of monopole searches w.r.t. cross section & charge

Supersymmetric long-lived particles

- Long-lived sleptons
  - gauge-mediated symmetry-breaking (GMSB)
  - may be slow-moving when produced at LHC

$$\Gamma(\tilde{l} \to l\tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{l}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^4$$

  - ☛ trigger-based searches may miss them in ATLAS and CMS
- Gluinos in Split Supersymmetry ➜ R-hadrons

$$R = \tilde{g}q\bar{q},\ \tilde{g}qqq,\ \tilde{g}g$$

  - long-lived because squarks very heavy
  - gluino hadrons may flip charge as they pass through matter
  - ☛ may be missed by ATLAS and CMS
- Moreover R-hadrons may be "trapped" in detector volumes decay at later times ➜ monitor volumes after testing for magnetic monopoles

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The physics programme of the MoEDAL experiment at the LHC

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Many more interesting theoretical scenarios relevant and accessible to MoEDAL not presented here:

- doubly-charged Higgs
- black-hole remnants
- quirks
- Q-balls
- CHAMPS
- ….

Complete and detailed review on MoEDAL impact on searches for exotic models

MoEDAL physics program:

IJMP A29 (2014) 1430050

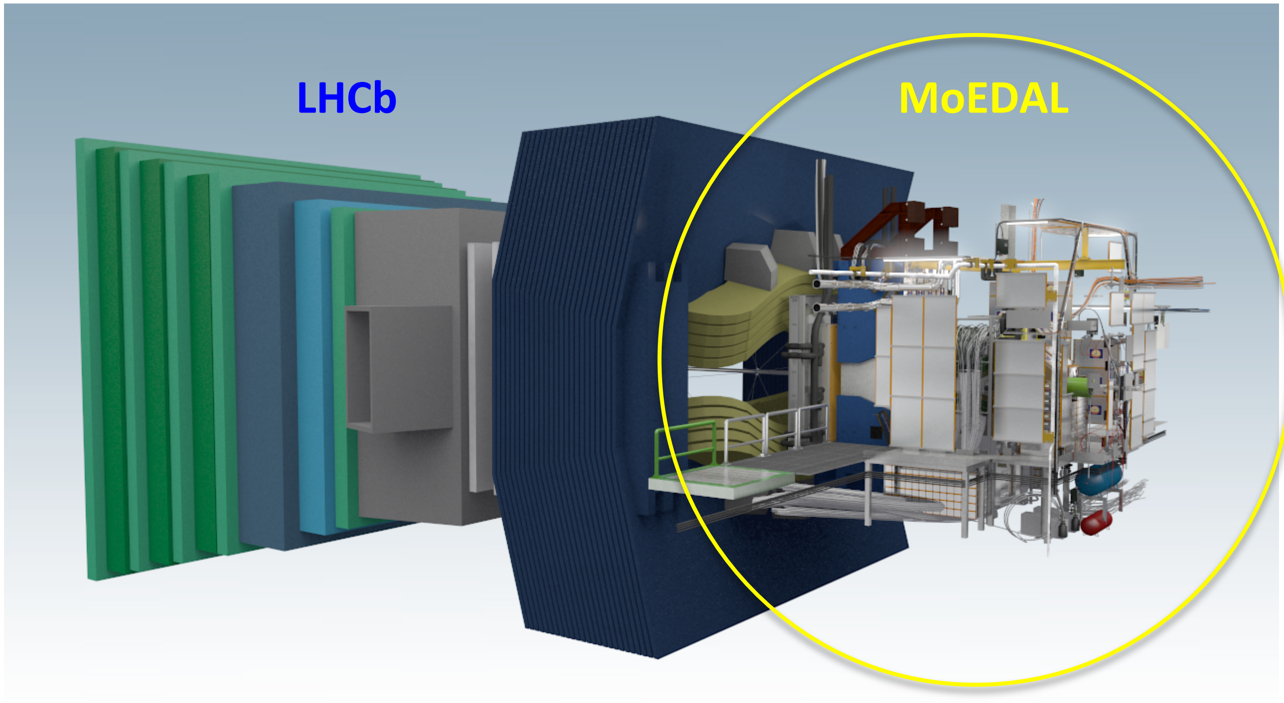
arXiv:1405.7662

MoEDAL web page:

http://moedal.web.cern.ch/

The MoEDAL detector

The MoEDAL detector



DETECTOR SYSTEMS

① Low-threshold NTD (**LT-NTD**) array
  - $Z/\beta > \sim 5$

② Very High Charge Catcher NTD (**HCC-NTD**) array
  - $Z/\beta > \sim 50$

③ TimePix radiation background monitor

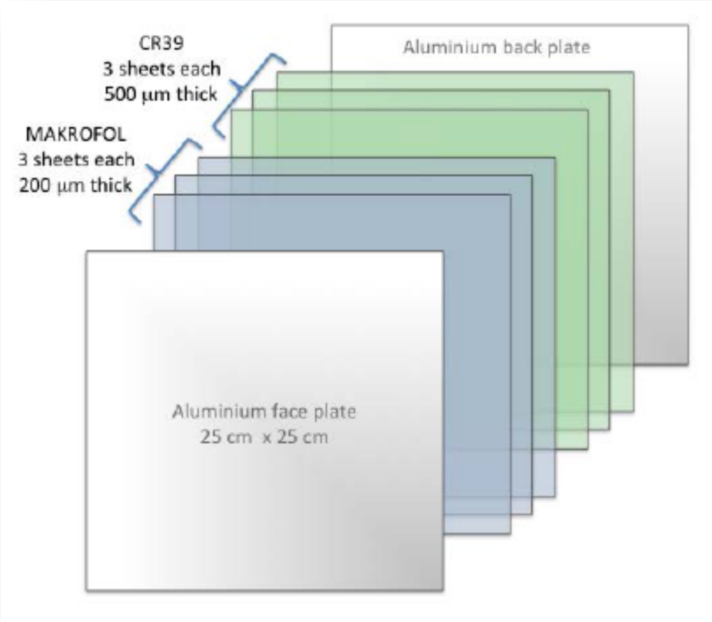
④ Monopole Trapping detector (**MMT**)

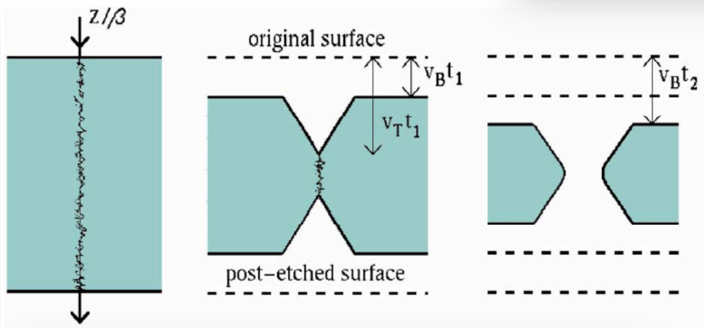
MoEDAL is unlike any other LHC experiment:

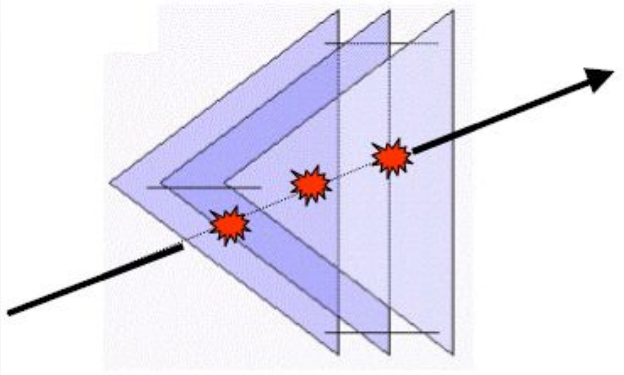
- mostly **passive detectors**; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- the 1st time **trapping detectors** are deployed as a detector

1 & 2 HI particle detection in NTDs

- The passage of a highly ionising particle through the plastic track-etch detector (e.g. CR39®) is marked by an invisible damage zone ("latent track") along the trajectory
- The damage zone is revealed as a cone-shaped etch-pit when the plastic detector is etched in a controlled manner using a hot sodium hydroxide solution



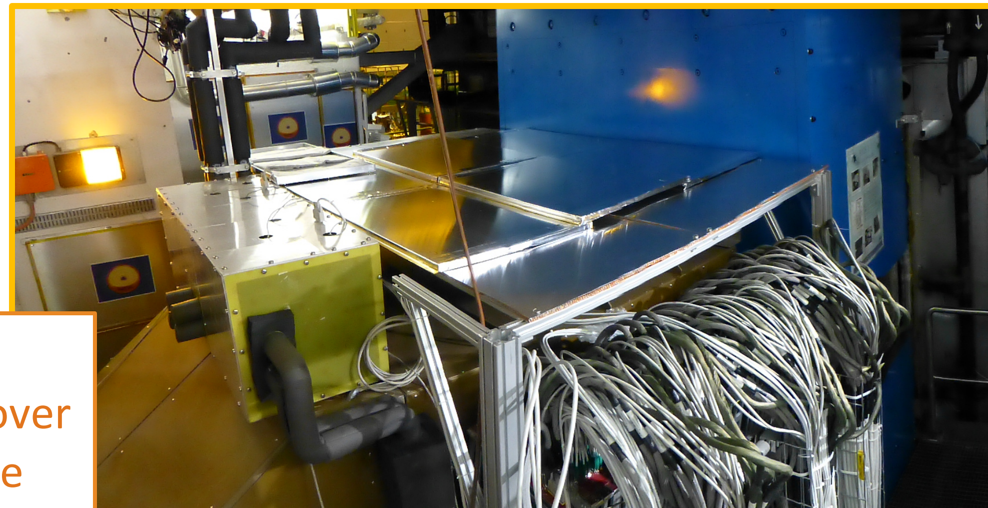




Looking for aligned etch pits in multiple sheets

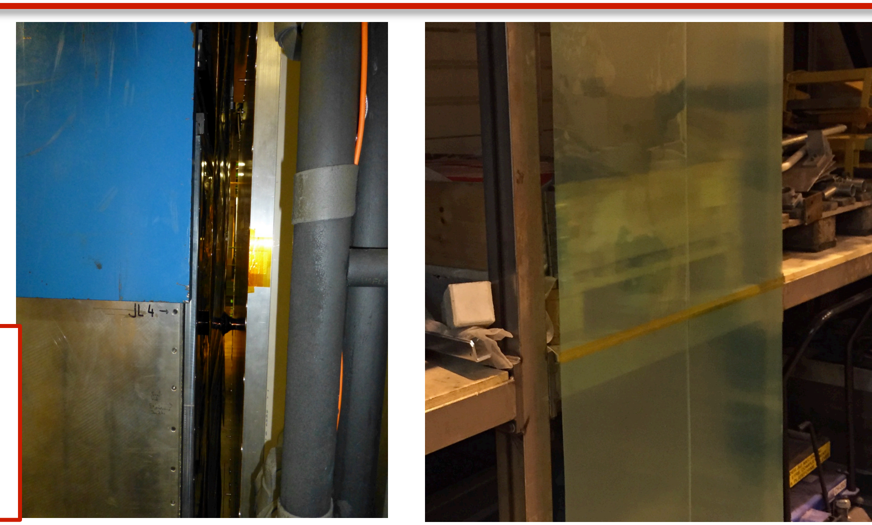
1 & 2 NTDs deployment

2012: LT-NTD
NTDs sheets kept in boxes mounted onto LHCb VELO cavern walls



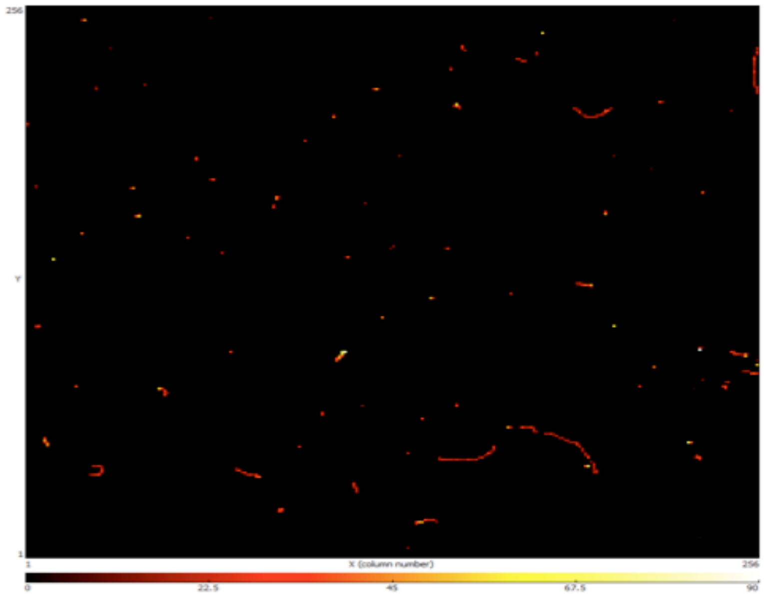
2015: LT-NTD
Top of VELO cover
Closest possible location to IP

2015: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT



3 TimePix radiation monitor

- Timepix (MediPix) chips are used to measure online the radiation field and monitor the spallation product background
- Essentially act as little electronic "bubble-chambers"



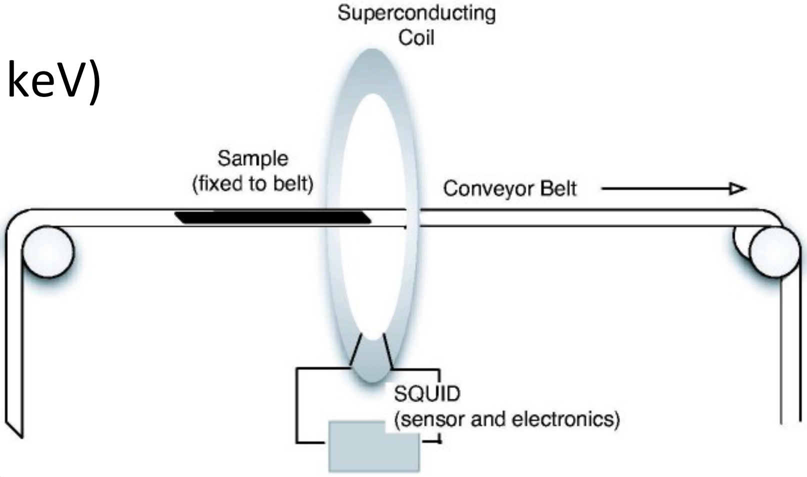
A screen capture of real-time output of an installed TimePix detector showing the radiation background conditions in the MoEDAL/VELO cavern with beam-off.

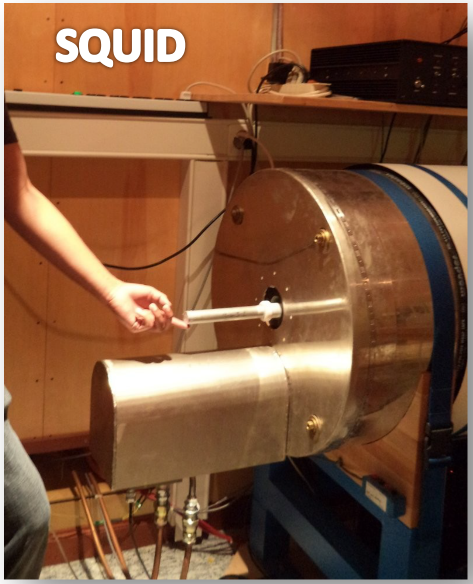
2015 deployment of MediPix chips in MoEDAL

- 256×256 pixel solid state detector
- 14×14 mm active area
- amplifier + comparator + counter + timer

4 MMT: Magnetic Monopole Trapper

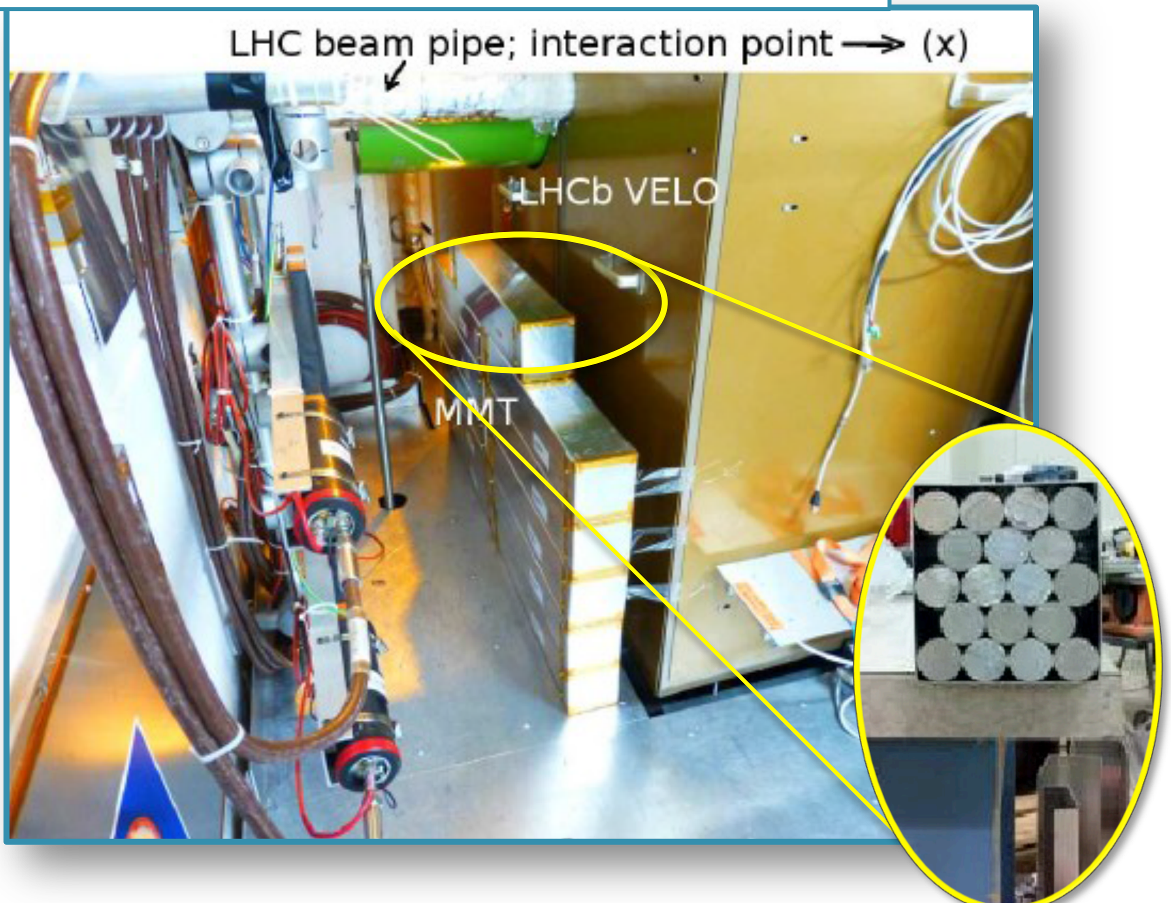
- Binding energies of monopoles in nuclei with finite magnetic dipole moments $\mathcal{O}$(100 keV)
- MMTs analysed with superconducting quantum interference device (SQUID)
- Material: Aluminium
  - large nuclear dipole moment
  - relatively cheap
- Disadvantage: rather low geometrical acceptance
- Advantages:
  - speed: SQUID measurements & analysis take ~2 weeks
  - complementarity: totally different concept from NTDs ➜ different systematic uncertainties
  - magnetic charge measurement with < 5% precision
  - **Bonus**: monitoring for decay products of trapped electrically-charged particles at underground laboratory





MMTs deployment

2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (**160 kg**)



2015
- Installed in new locations
- Approximately **800 kg** of Al
- Total 2400 pieces

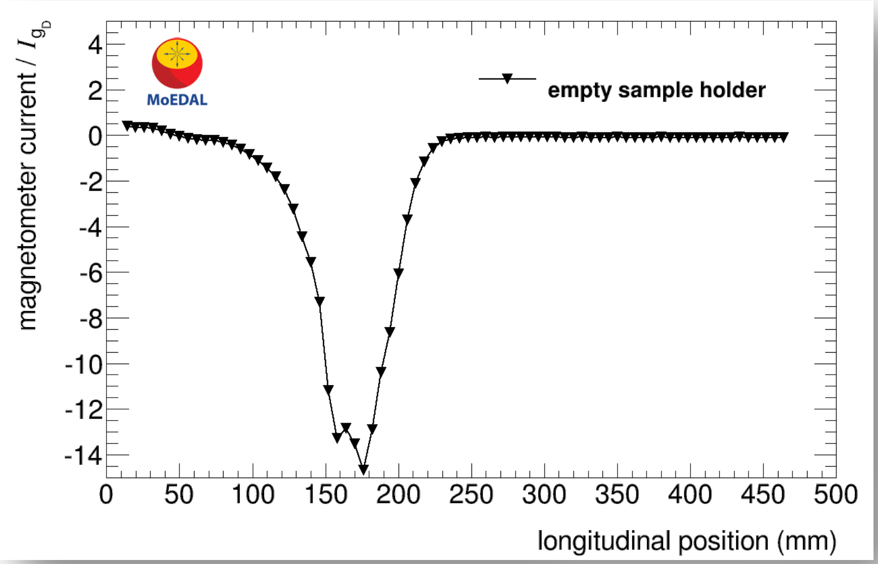
Results on monopole mass & charge from MMT 2012 run

Recently released!

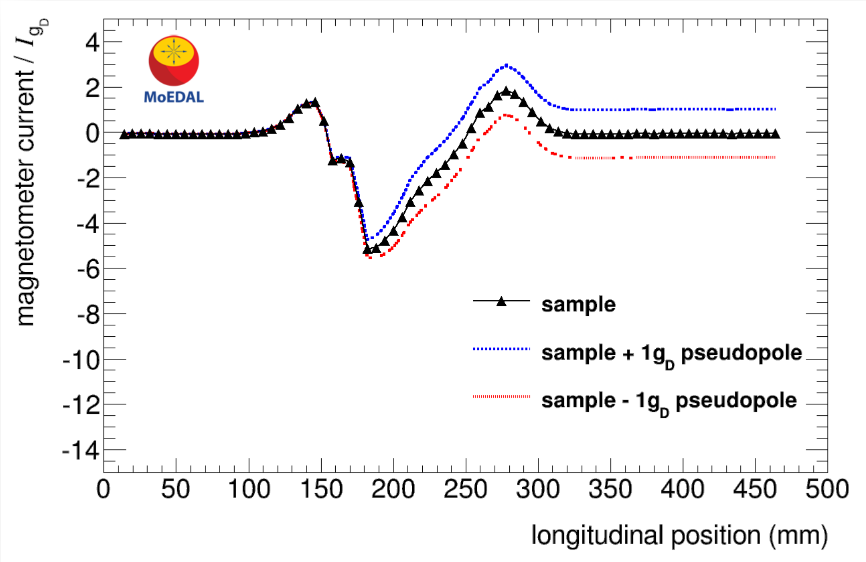
arXiv:1604.06645

Magnetometer measurement procedure

- Output measured before, during, and after passage of sample through sensing coil
- Subtract measurement with empty holder
- **Persistent current:** difference between resulting current after and before
  - if other than zero → monopole signature



Sample holder only



Typical sample after subtracting holder

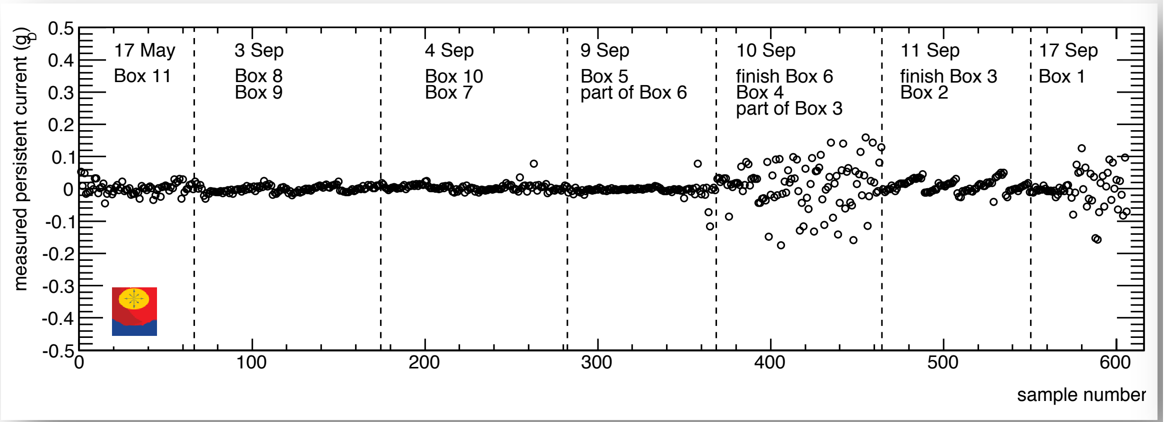
MMT 2012 analysis

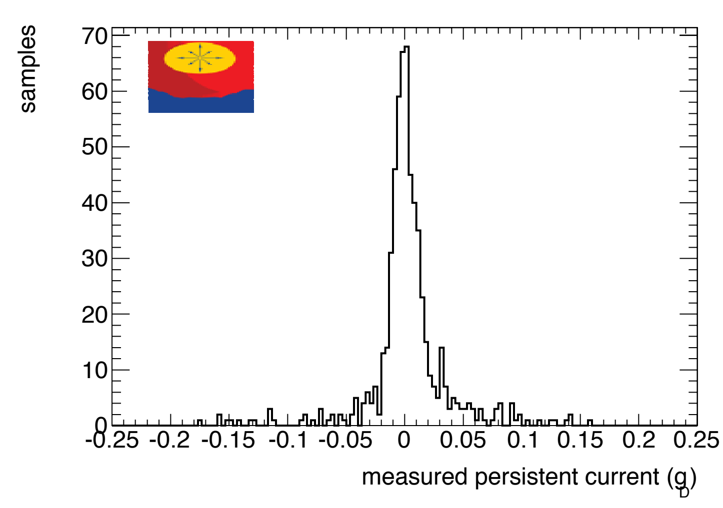
Exposure: **0.75 fb^{-1}** of **8 TeV** *pp* collisions

- Analysed with SQUID at ETH Zürich
- Excellent charge resolution (< 0.1 g_D) except for outliers
  - small occasional (2%) offset jumps due to known instrumental effects
  - multiple measurements of outliers yield currents consistent with zero

arXiv:1604.06645

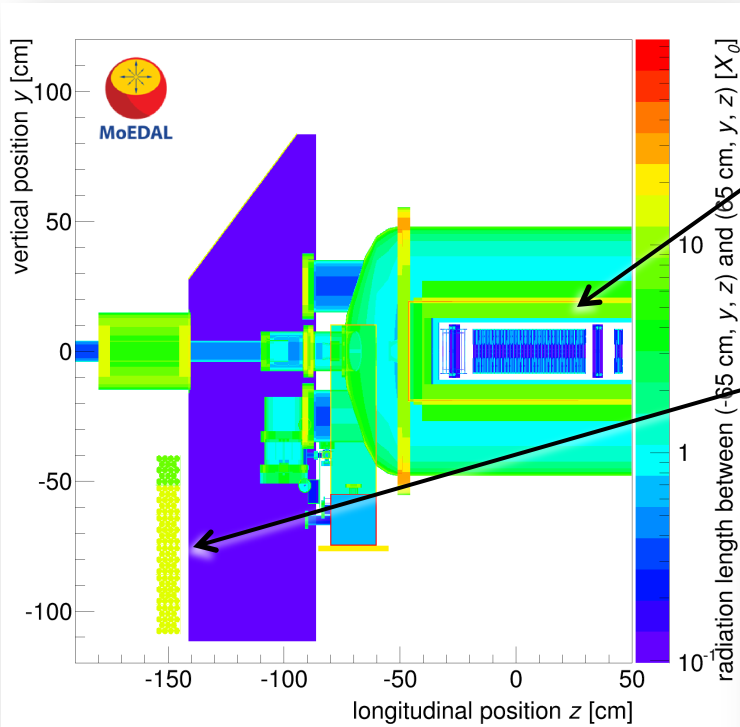
Persistent current after first passage for all samples





No monopole with charge > 0.5 g_D observed in MMT at 99.75% CL

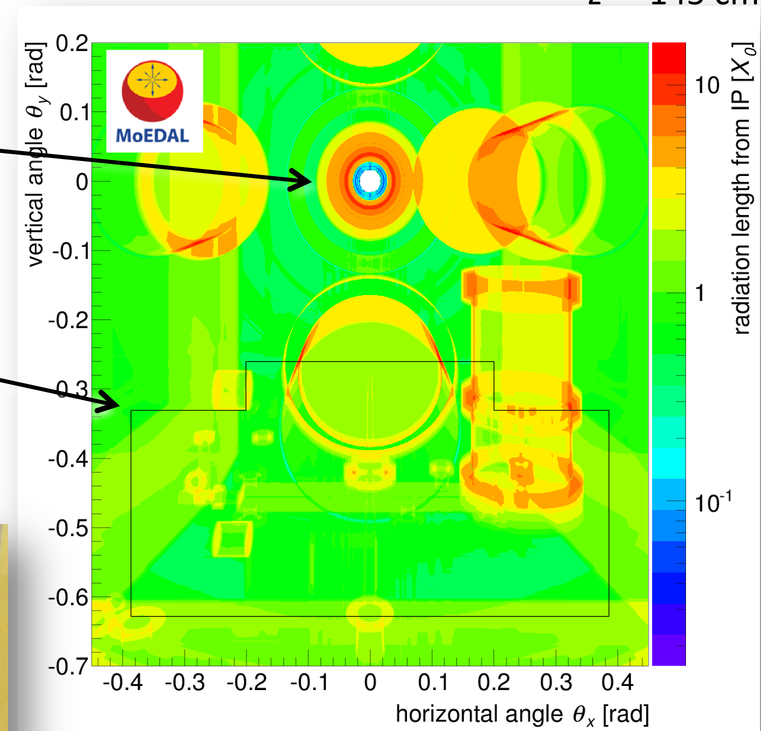
Geometry description



LHCb VErtex Locator (VELO)

MMT coverage

z = -145 cm



- Good knowledge of material between IP and detector essential to determine monopole stopping position

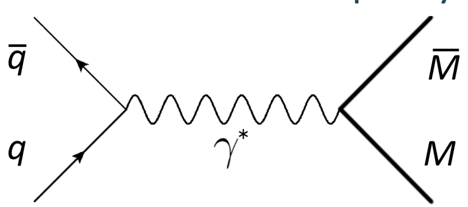
- Geant4 used for simulating monopole propagation in the material

arXiv:1604.06645

Monopole event generation

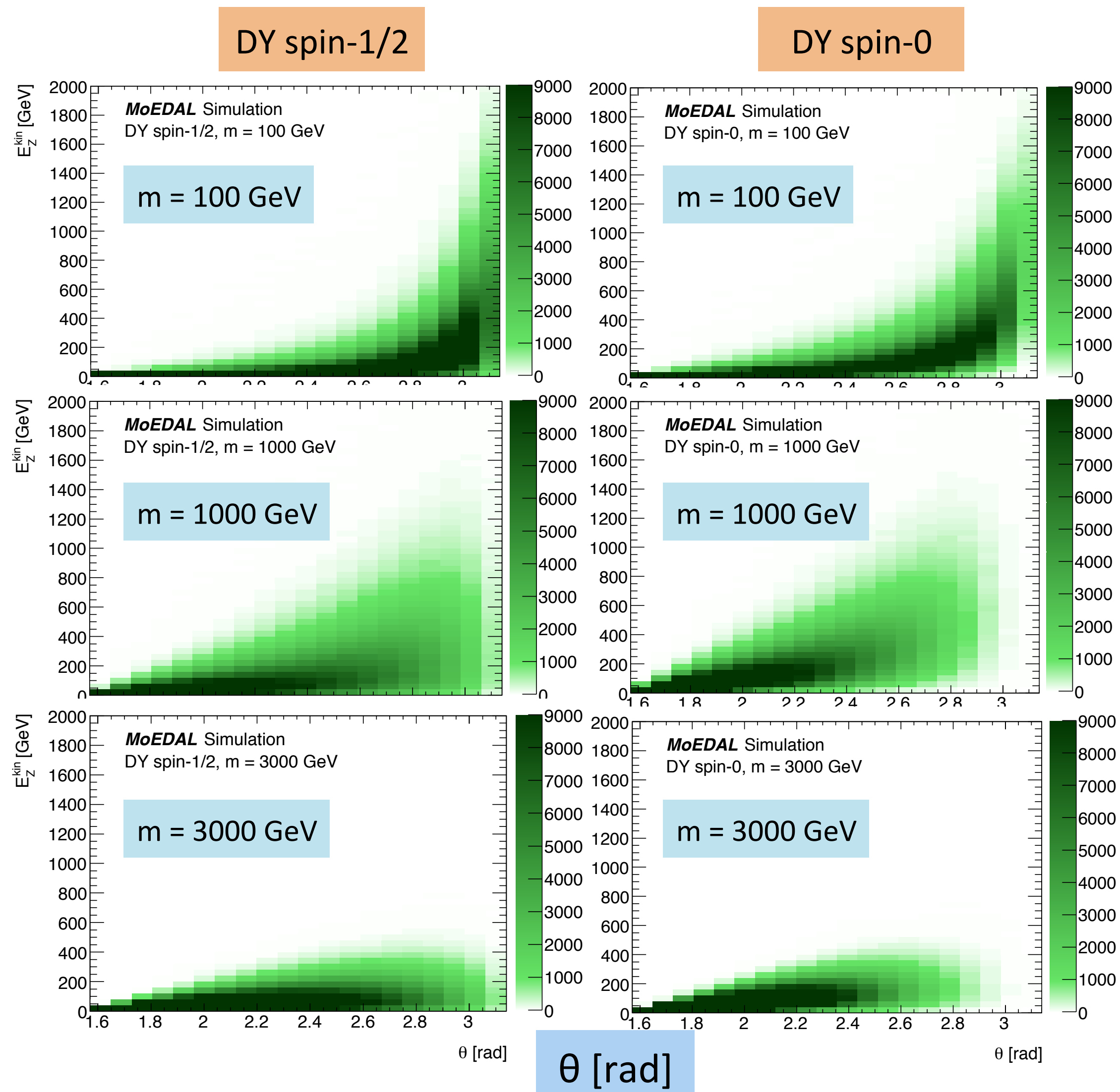
Two production processes

- **single-monopoles** with flat θ, ϕ and E_{kin} distributions
  - used to set model-independent limits
- **pair production**: Drell-Yan model, spin-½ and spin-0 monopoles
  - give different kinematics
  - chosen for its simplicity



$$E_Z^{kin} = E^{kin} \sin\theta$$

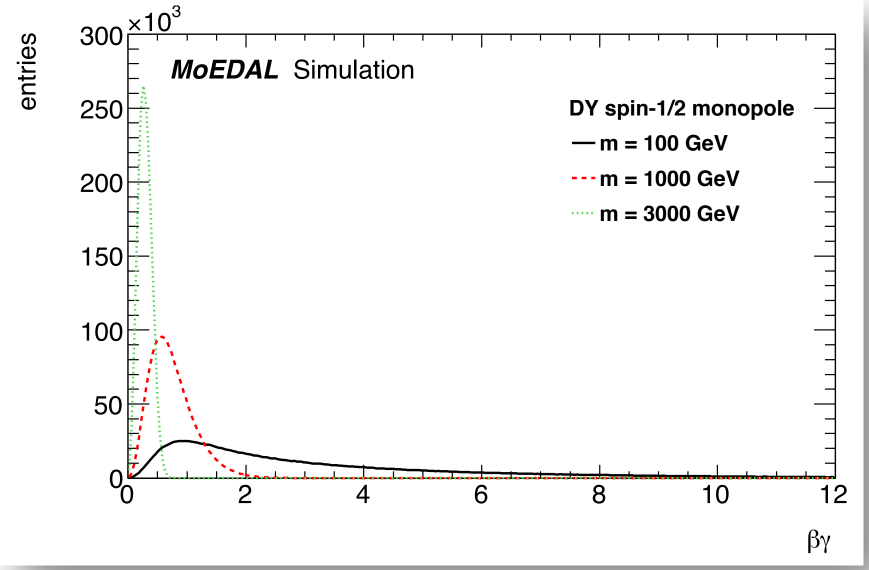
arXiv:1604.06645

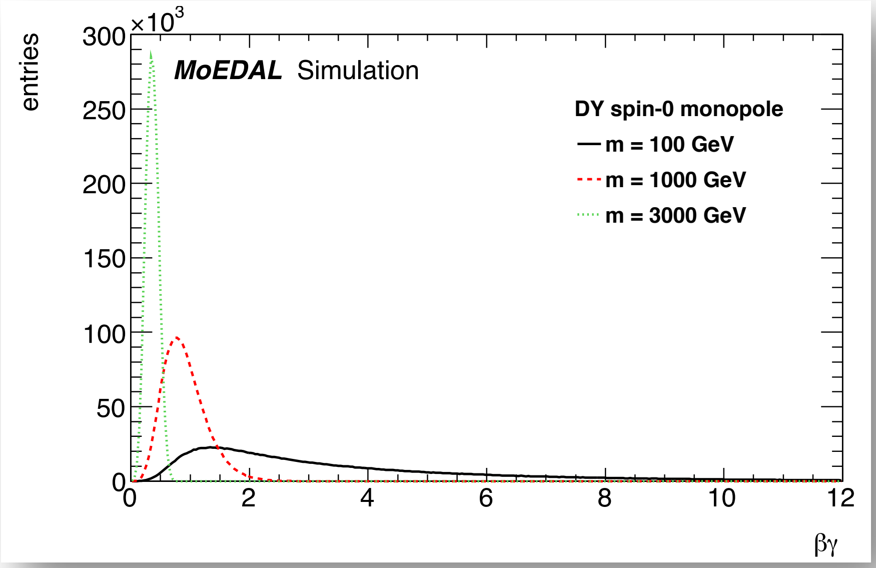


Simulation of monopole propagation

- Handled by Geant4 within LHCb software framework
- Acceleration in magnetic field implemented, but not relevant for 2012 trapping detector location
- Velocity dependence of ionisation energy loss in matter implemented for magnetic charge: modified Bethe-Bloch, Ahlen formulas and interpolations
- Trapping criterion: $\beta < 10^{-3}$; tested with 10^{-2} limit
- Radiative effects significant only for $\beta\gamma > 70$ → neglected

arXiv:1604.06645





Trapping acceptance – Drell-Yan production

- Acceptance = probability (per event) that at least one monopole stops in the trapping detector
- Obtained by propagating pair-produced monopoles through geometry description for each mass and charge
- Uncertainties in acceptance estimated for each mass and charge separately
  - MC statistics: 1-9%
  - dE/dx systematics $\beta < 0.1$ region: 1-9%
  - dE/dx systematics $\beta > 0.1$ region: 1-7%
  - MMT position systematics: 1-17%
  - material budget systematics: 1-100% (dominant)
- Charge and mass points with > 100% systematics (corresponding to < 0.1% acceptance) not included
  - this is the case for $5g_D$ and $6g_D$ (all masses)
  - also for $3g_D$ and $4g_D$ low and high masses

arXiv:1604.06645

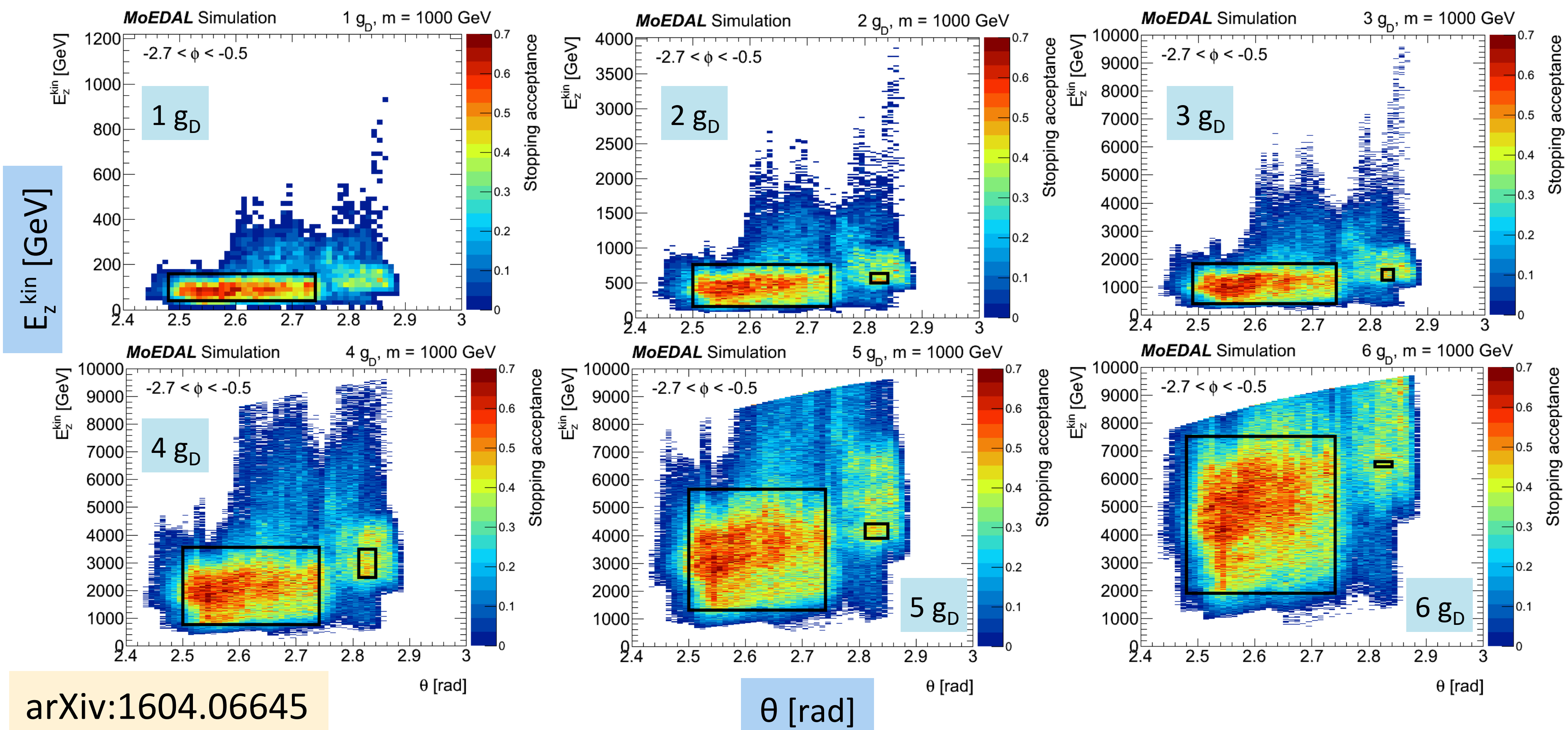
Trapping acceptance – Drell-Yan production

spin	m [GeV]	$\lvert g\rvert = g_D$	$\lvert g\rvert = 2g_D$	$\lvert g\rvert = 3g_D$	$\lvert g\rvert = 4g_D$
½	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	—	—
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	—	—

arXiv:1604.06645

Trapping acceptance – model-independent

- Estimating detector acceptance without model assumption for monopole kinematics
- Map in E_z^{kin} versus θ, averaged over $-2.7 < \phi < -0.5$ (MMT2012 coverage)
- Fiducial regions: rectangles with 40% average efficiency and < 15% standard deviation



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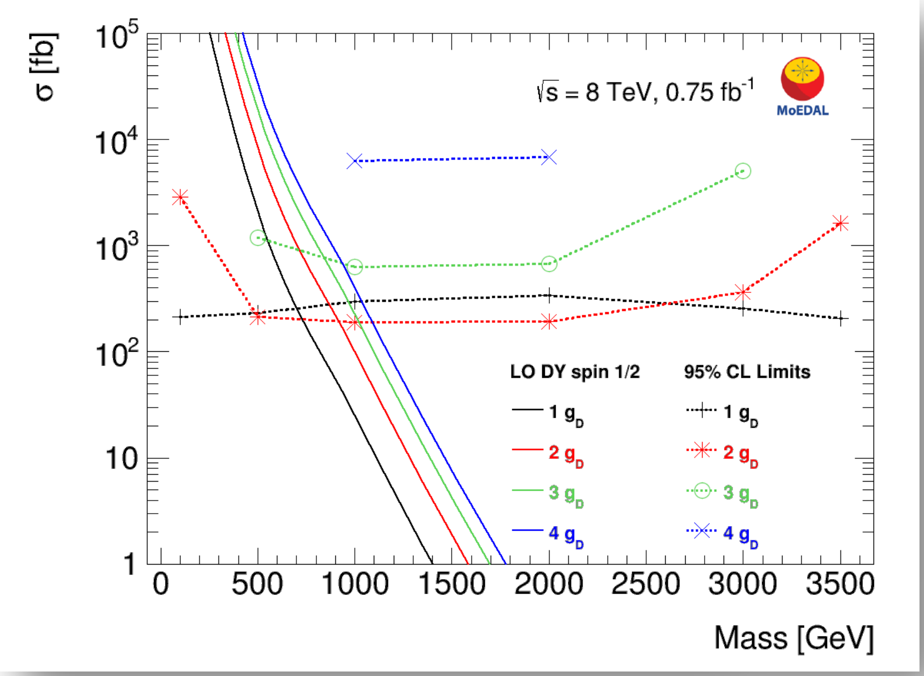
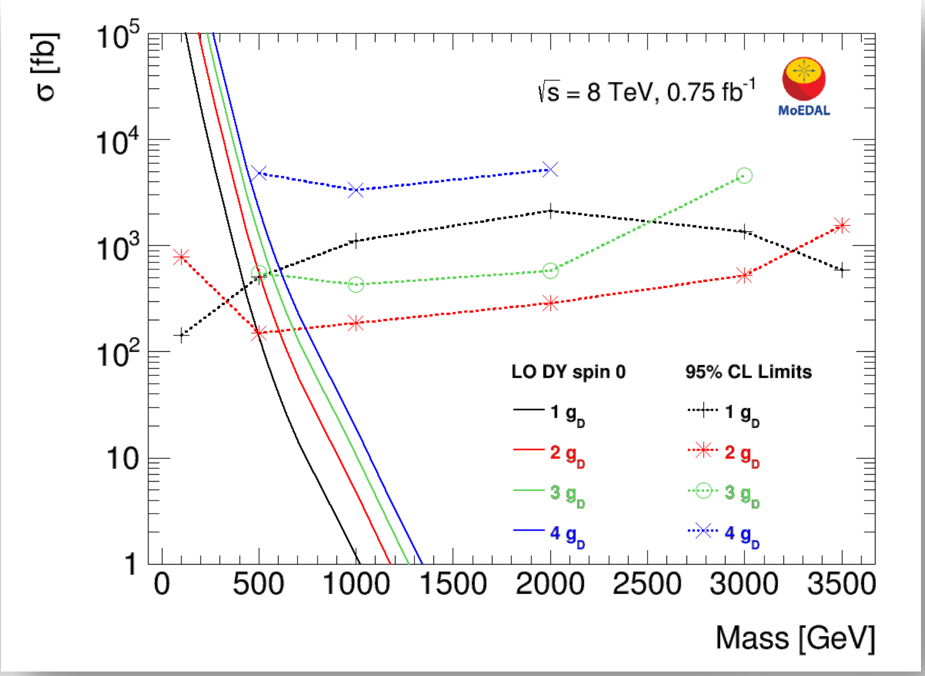
Cross section limits versus mass



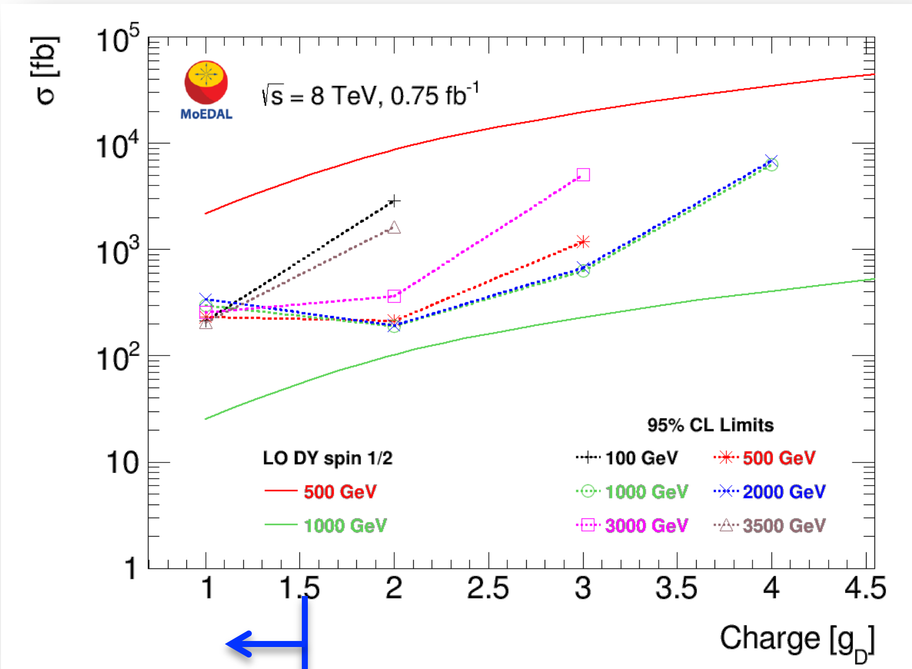


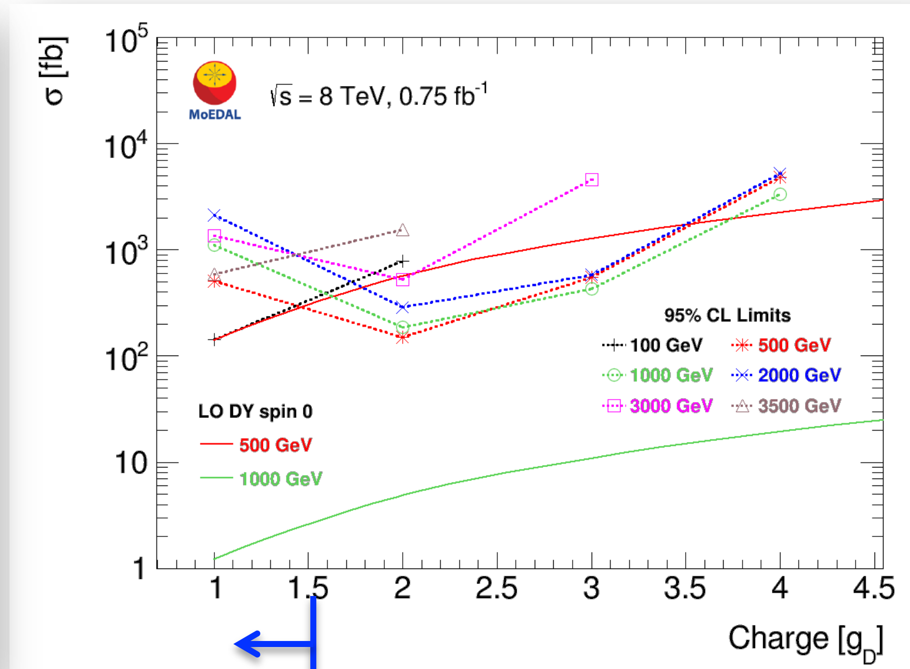
Limits extend up to masses > 2500 GeV for the first time at the LHC

- reminder: shown (tiny) LO DY cross sections are not reliable
  ⇒ makes sense to probe and constrain very high masses

arXiv:1604.06645

Cross section limits versus charge





also covered by ATLAS search

Limits extend up to magnetic charge > $1.5g_D$

- **first time at the LHC**
- up to $4g_D$

arXiv:1604.06645

Mass & cross-section limits

arXiv:1604.06645

- Mass limits are *highly model-dependent*
  - Drell-Yan production does take into account non-perturbative nature of the large monopole-photon coupling

DY lower mass limits [GeV]	$\lvert g\rvert = g_D$	$\lvert g\rvert = 2g_D$	$\lvert g\rvert = 3g_D$
spin ½	700	920	840
spin 0	420	600	560

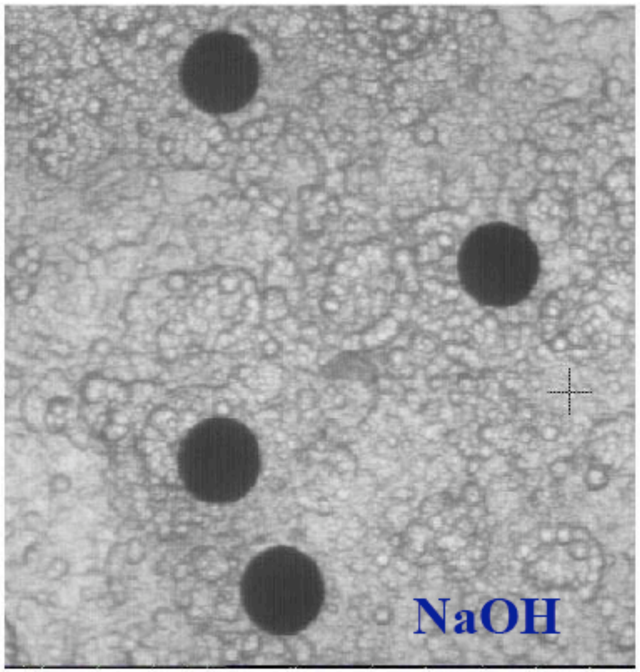
- Limits for $|g| = g_D$ weaker than recent ATLAS 8 TeV analysis (for same production assumptions):
  - 1340 GeV for spin-1/2 and 1050 GeV for spin-0 [arXiv:1509.08059]
- **World-best limits for $|g| > g_D$**
  - previously ~400 GeV at Tevatron [e.g. CDF hep-ex/0509015]
- **Model-independent upper limit of 10 fb on monopole production with charge up to $6g_D$**

Summary & outlook

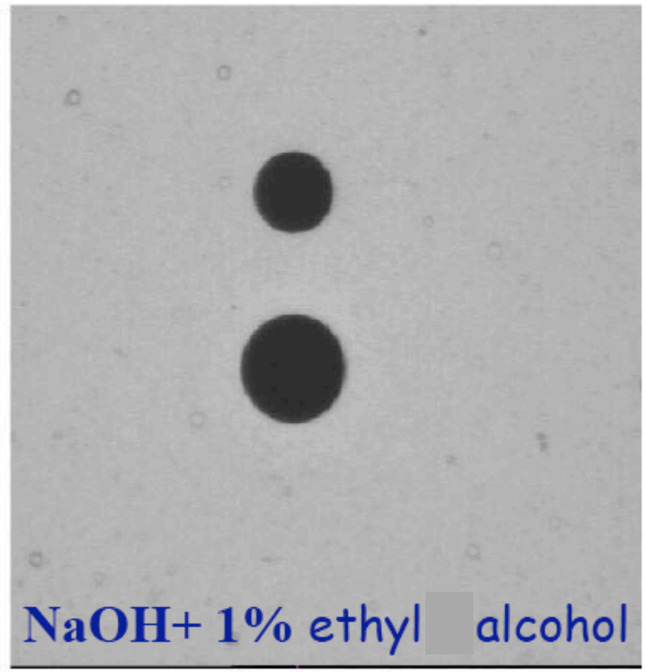
- MoEDAL is searching for **(meta)stable highly ionising particles**
  - least tested signals of New Physics
  - predicted in variety of theoretical models
  - design optimised for such searches
    - unlike other LHC experiments
  - combining various detector technologies
- First physics results just been released… `arXiv:1604.06645`
- Looking forward to new results from LHC Run-II

Spares

NTD scanning results



(a) Makrofol etched in 6N NaOH at 50 C for 95 hours

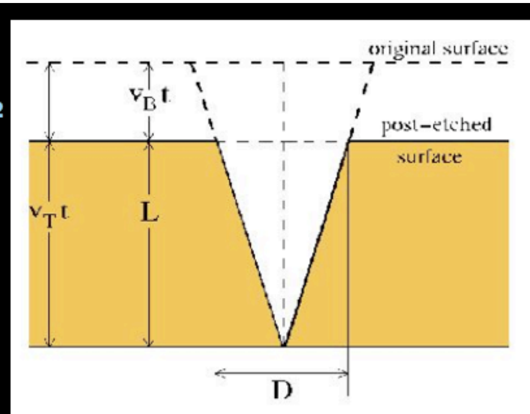


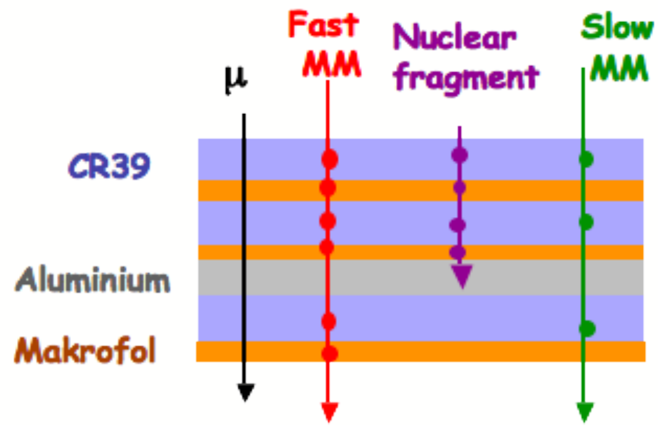
(b) Makrofol etched in 6N KOH with addition of 20% ethyl alcohol by volume for 8 hours

Evident that with KOH the surface defects are drastically reduced and the sheets are more transparent

Analysis procedure

- Track diameter:
  - $D = 2v_B[(v_T-v_B)/(v_T+v_B)]^{-1/2}$
- Track depth:
  - $L = (v_T-v_B)\, t$
- Reduced etch rate:
  - $p = v_T/v_B$





- Electrically-charged particle: $dE/dx \sim \beta^{-2}$ ➔ slows down appreciably within NTD ➔ opening angle of etch-pit cone becomes **smaller**
- Magnetic monopole: $dE/dx \sim \ln\beta$
  - slow MM: slows down within an NTD stack ➔ its ionisation falls ➔ opening angle of the etch pits would become **larger**
  - relativistic MM: dE/dx essentially constant ➔ trail of equal diameter etch-pit pairs
- The reduced etch rate is simply related to the *restricted energy loss* $REL = (dE/dx)_{\text{10nm from track}}$

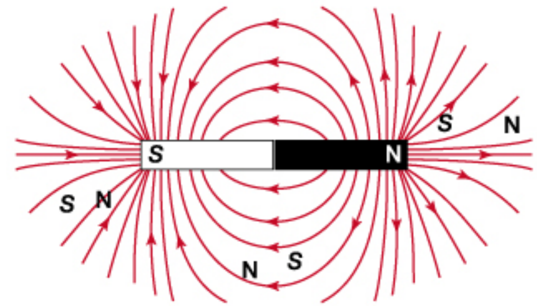
Dirac's Monopole

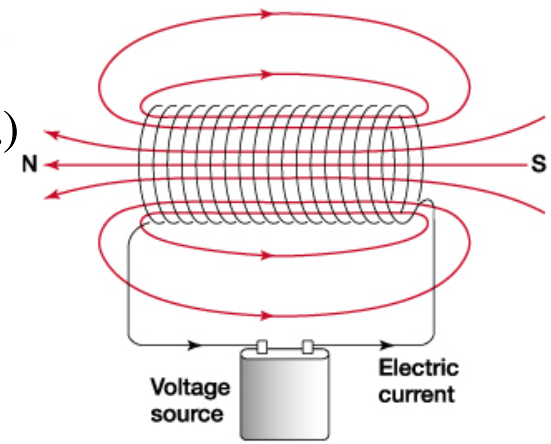
- Paul Dirac in 1931 hypothesized that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac's quantisation condition:

$$ge = \left[\frac{\hbar c}{2}\right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad \left(from \ \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

- Where g is the "magnetic charge" and α is the fine structure constant 1/137
- This means that **g = 68.5e** (when n=1)!
- The other way around: IF there is a magnetic monopole then charge is quantised:

$$e = \left[\frac{\hbar c}{2g}\right] n$$



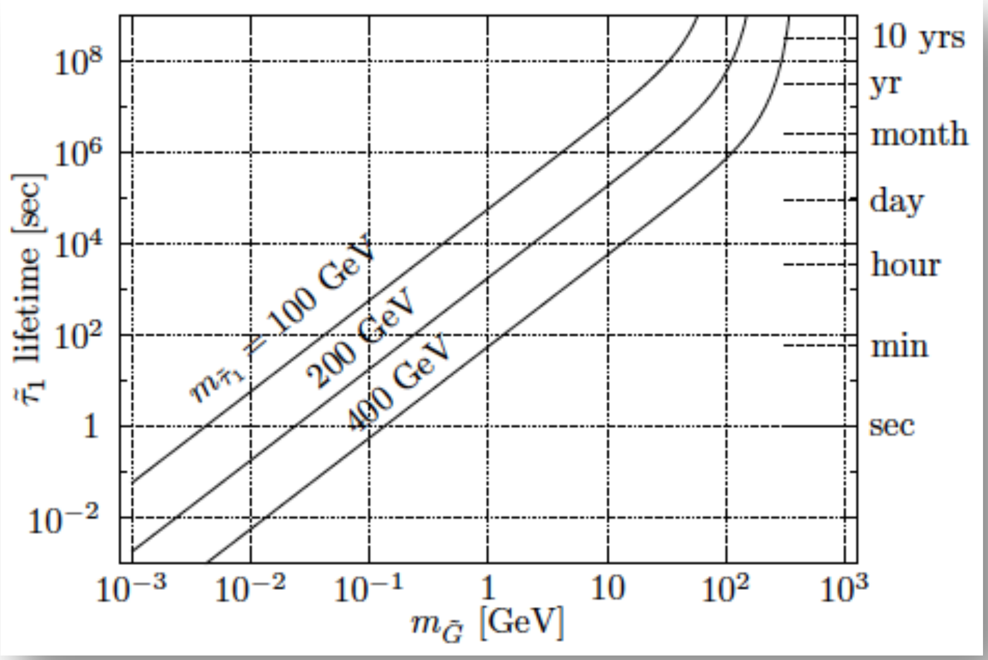


Dirac String

Long-lived sleptons

- Gauge-mediated Supersymmetry-Breaking (GMSB)
- Stau NLSP decays via gravitational interaction to gravitino LSP
  ➜ naturally long lifetime
  ➜ LSP dark matter candidate
- Long-lived staus
  - also in coannihilation region with Lepton Flavour Violation
  - may be slow-moving when produced at LHC
  - ➜ high ionisation

$$\Gamma(\tilde{l} \to l\tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{l}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^4$$



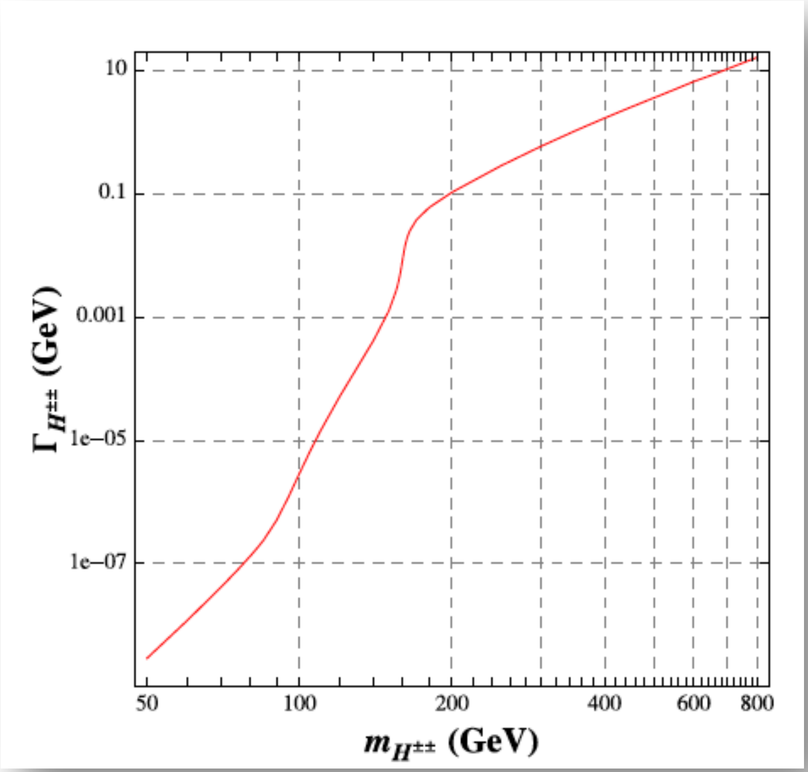
Hamaguchi, Nojiri, De Roeck,
JHEP 0703 (2007) 046 [hep-ph/0612060]

average distance travelled

$$L = \frac{1}{\kappa_\gamma}\left(\frac{100\text{GeV}}{m}\right)^5\left(\frac{\sqrt{F/k}}{100\text{TeV}}\right)^4\sqrt{\frac{E^2}{m^2}-1} \times 10^{-2}cm \quad \sqrt{F} \gtrsim 10^6 \text{ GeV}$$

Doubly-charged Higgs

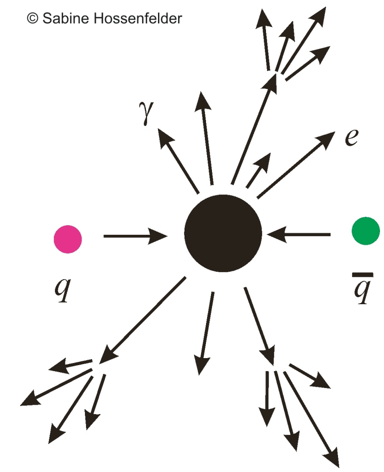
- Extended Higgs sector in BSM models: $SU_L(2) \times SU_R(2) \times U_{B-L}(1)$ P-violating model
- Higgs triplet model with massive left-handed neutrinos but not right-handed ones
- Common feature: **doubly charged Higgs bosons $H^{\pm\pm}$** as parts of a Higgs triplet
- Lifetime
  - depends on many parameters: Yukawa h_{ij} (long if < 10^{-8}), $H^{\pm\pm}$ mass, ...
  - essentially there are no constraints on its lifetime ➜ relevant for MoEDAL



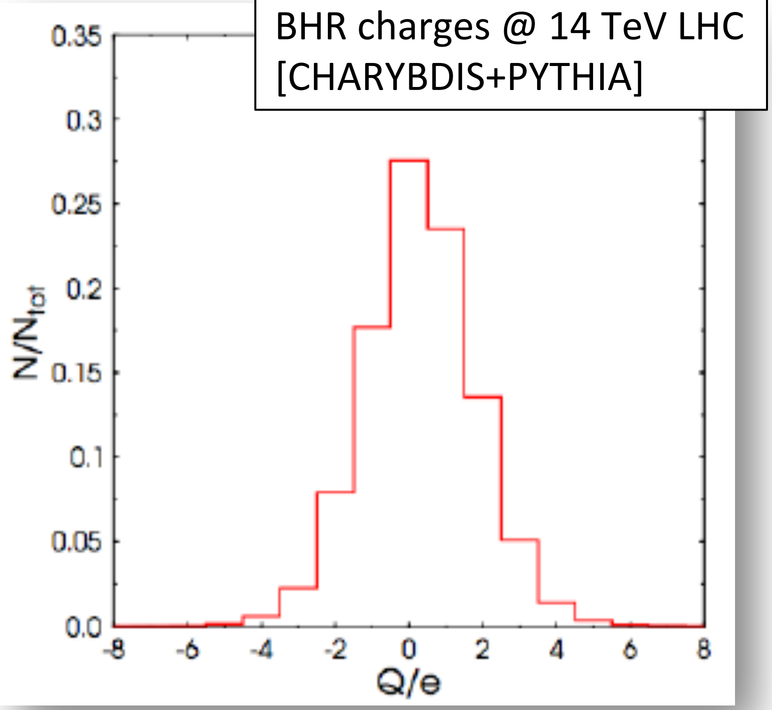
Partial decay width of $H^{\pm\pm} \to W^{\pm}W^{\pm}$

Chiang, Nomura, Tsumura,
Phys.Rev. D85 (2012) 095023 [arXiv:1202.2014]

Black-hole remnants



- Large Extra dimension models proposed to address the hierarchy problem:
  - electroweak scale $\mathcal{O}$(100 GeV)
  - gravitational (Planck) scale $M_{Pl} = \mathcal{O}(10^{16}$ TeV)
- Formation of TeV Black Holes (BH) by high energy SM particle collisions
  - BH average charge 4/3
  - slowly moving ($\beta \lesssim 0.3$)
- Charged Hawking BH evaporate but not completely
  ➜ certain fraction of final BH remnants carry **multiple charges ($BH^{\pm}$)**
  ➜ highly ionising, relevant to MoEDAL



Hossenfelder, Koch, Bleicher, hep-ph/0507140