Status, results and prospects from the MoEDAL experiment at LHC

Vasiliki A. Mitsou

for the MoEDAL Collaboration

16th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

Summer School and Workshop on the Standard Model and Beyond

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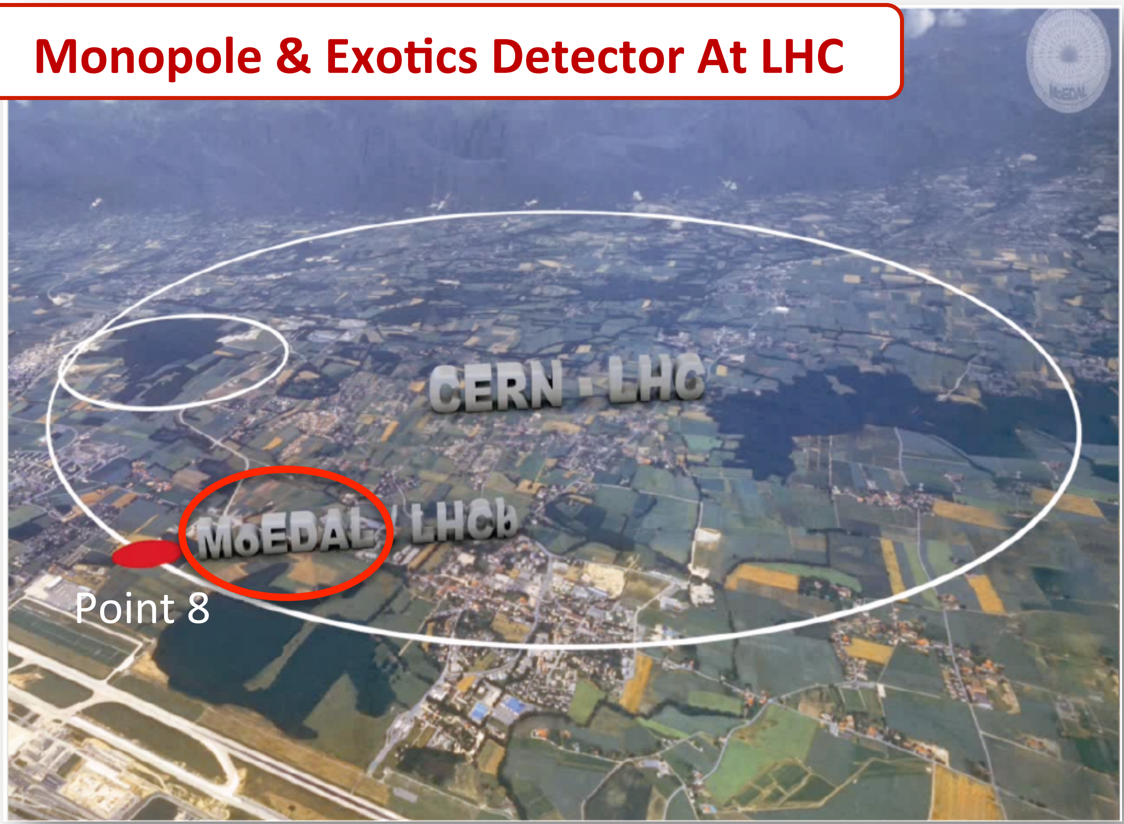
MoEDAL at LHC

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
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF HELSINKI
IMPERIAL COLLEGE LONDON
KING'S COLLEGE LONDON
KONKUK UNIVERSITY
UNIVERSITY OF MÜNSTER
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY
NORTHEASTERN UNIVERSITY
TECHNICAL UNIVERSITY IN PRAGUE
INSTITUTE FOR SPACE SCIENCES, ROMANIA
STAR INSTITUTE, SIMON LANGTON SCHOOL
TUFT'S UNIVERSITY
IFIC VALENCIA

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 (HI) possible when:

- multiple electric charge (H^{++}, Q-balls, etc.) = n × e
- very low velocity & electric charge, i.e. Stable Massive Charged Particles (SMCPs)
- 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**

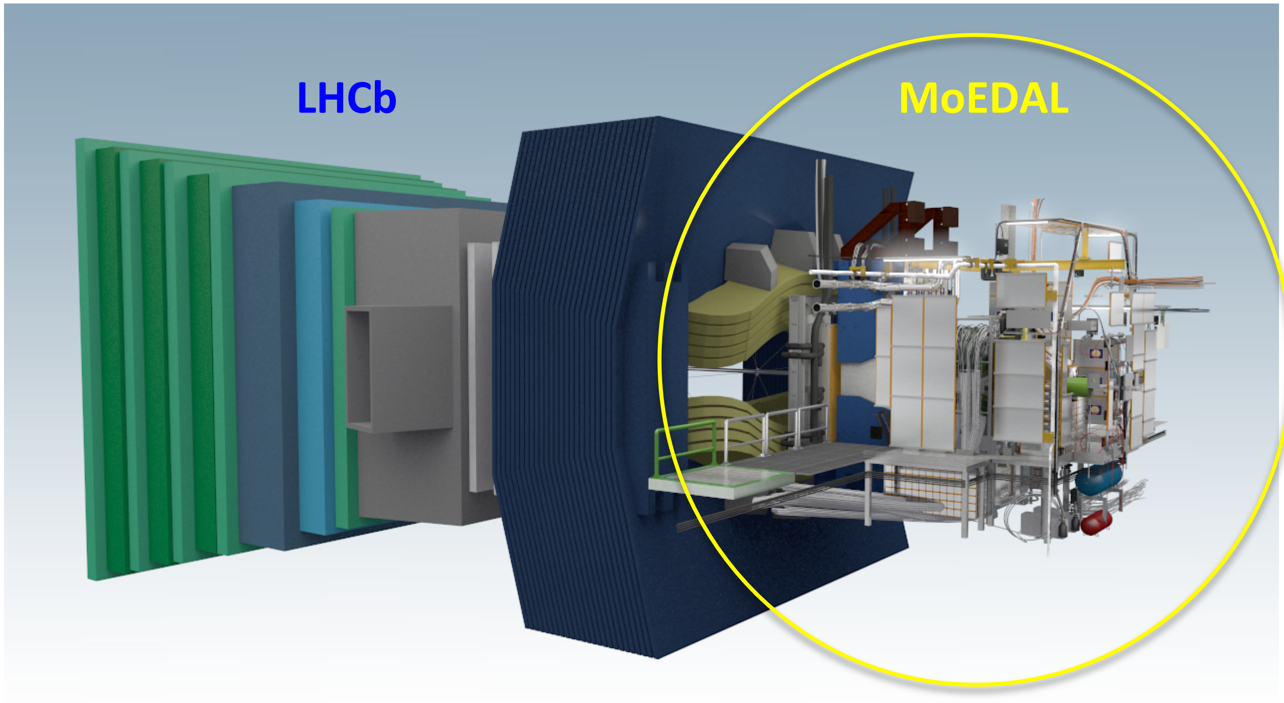
$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I_m} + \frac{K|g|}{2} - \frac{1}{2} - B(g)\right]$$

Magnetic charge
Ahlen formula

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

The MoEDAL detector components

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

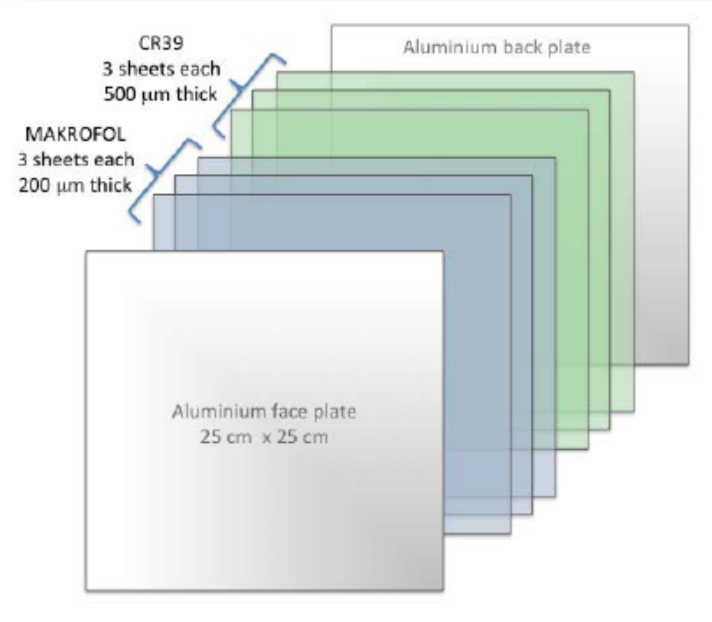
④ Monopole Trapping detector (**MMT**)

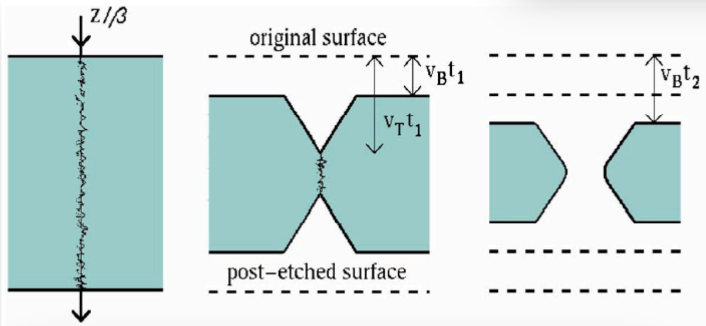
MoEDAL is unlike any other LHC experiment:

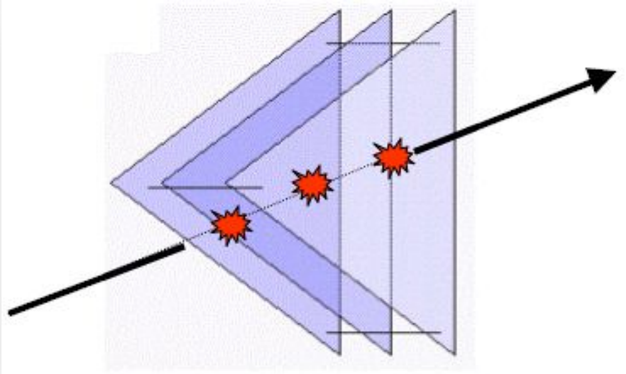
- mostly **passive detectors**; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- the 1st time **trapping detectors** are deployed as a detector

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
- Plastic sheets are later **scanned** to detect the etch-pits



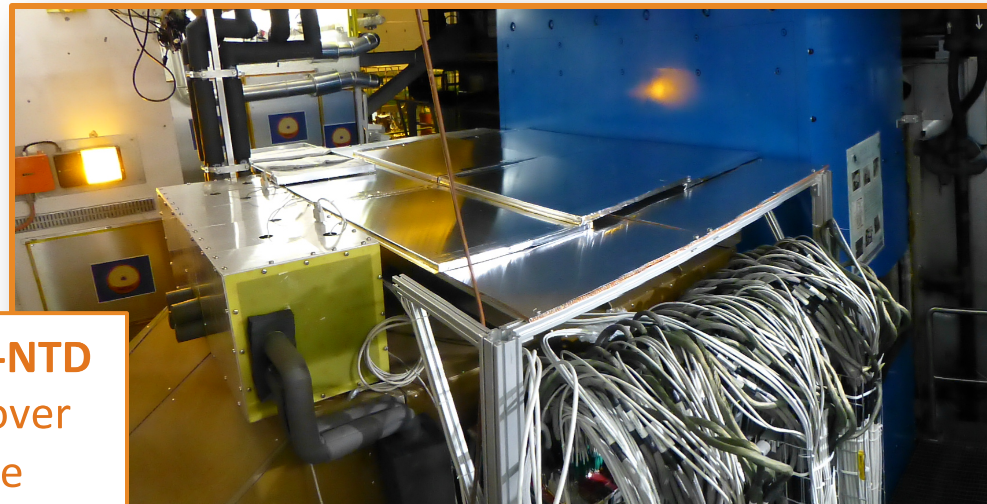




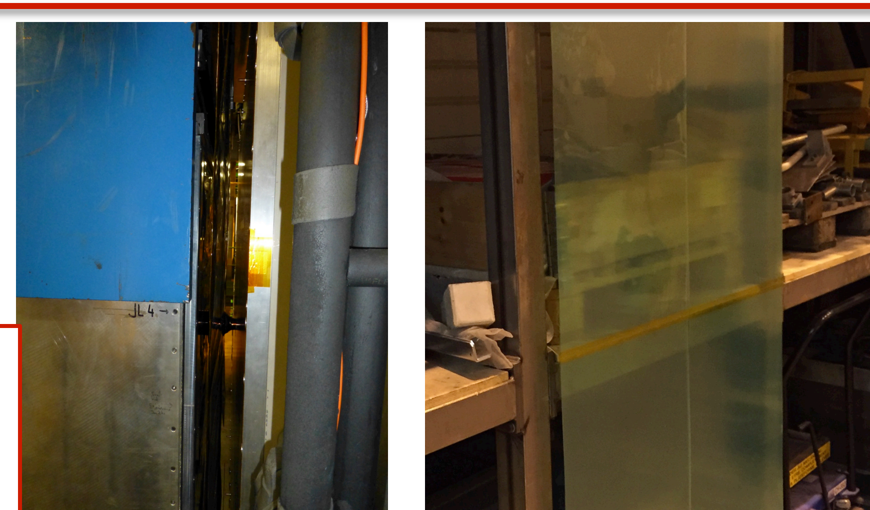
Looking for aligned etch pits in multiple sheets

1 & 2 NTDs deployment

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



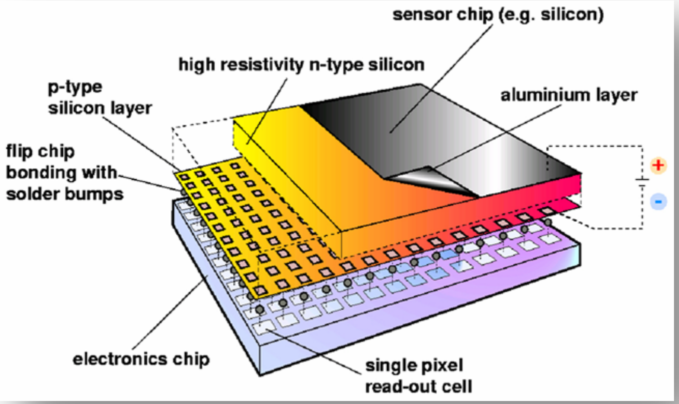
2015-2016: LT-NTD
Top of VELO cover
Closest possible location to IP

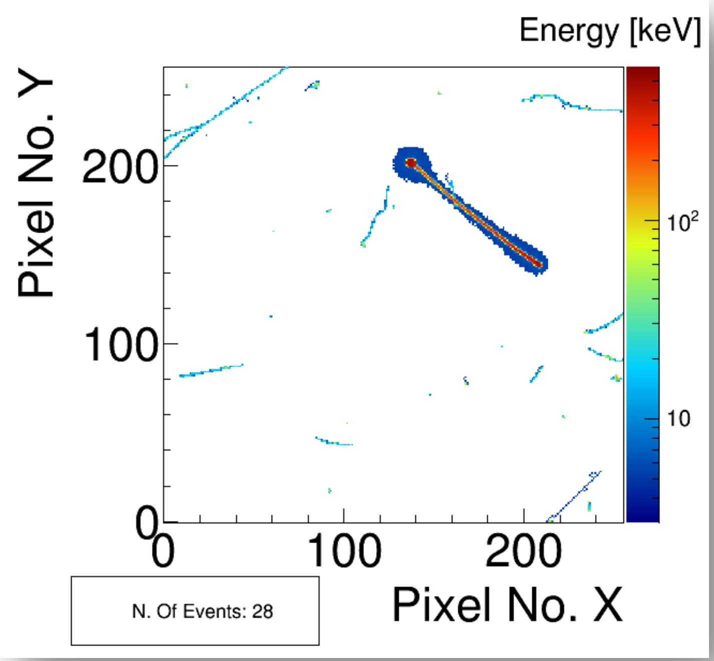


2015-2016: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT

3 TimePix radiation monitor

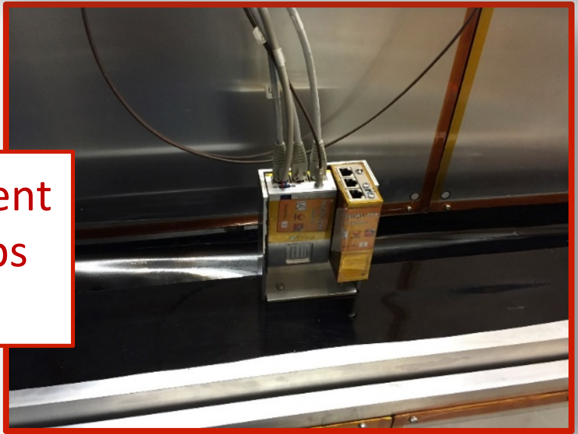
- Timepix (MediPix) chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic “bubble-chambers”
- The only active element in MoEDAL





Sample calibrated frame in MoEDAL TPX04

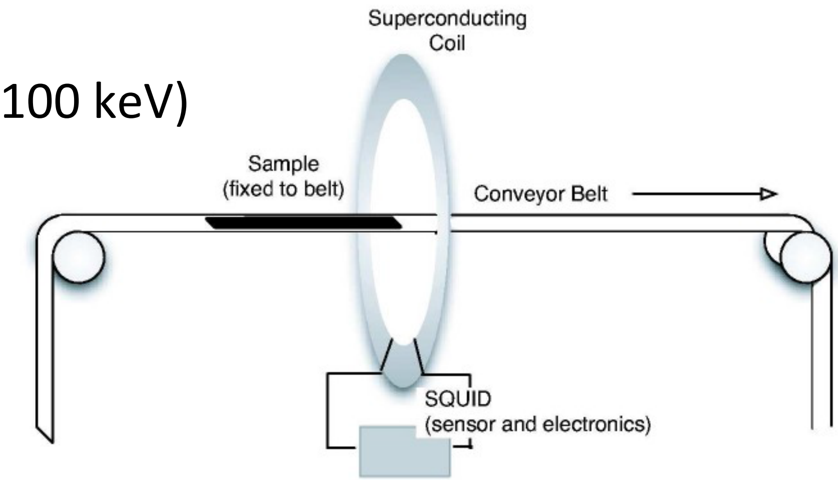
2015 deployment of MediPix chips in MoEDAL

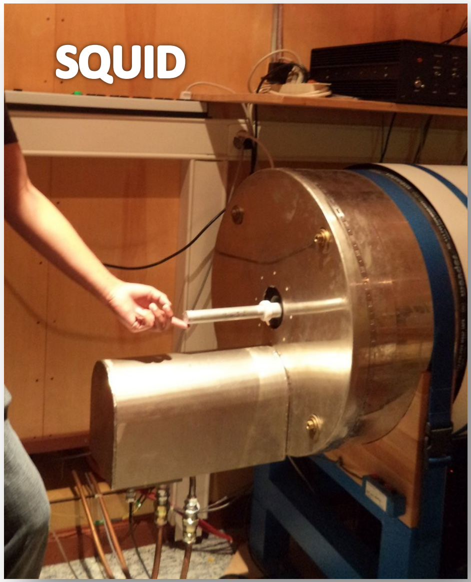


- 256×256 pixel solid state detector
- 14×14 mm active area
- amplifier + comparator + counter + timer

4 MMT: Magnetic Monopole Trapper

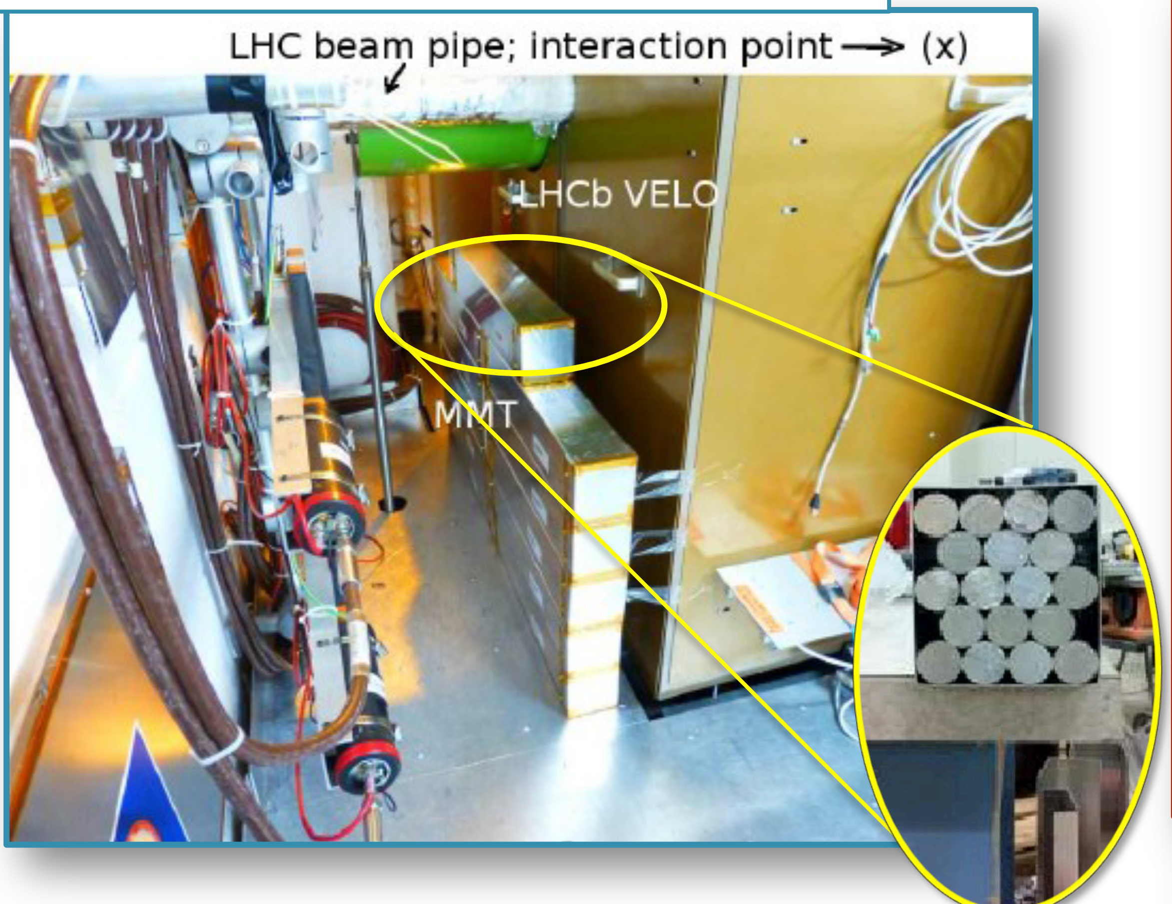
- Binding energies of monopoles in nuclei with finite magnetic dipole moments of $\mathcal{O}$(100 keV)
- MMTs analysed with superconducting quantum interference device (SQUID)
- Material: Aluminium
  - large nuclear dipole moment
  - relatively cheap
- Disadvantage: rather low geometrical acceptance
- 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**)



2015-2016
- Installed in new locations
- Approximately **800 kg** of Al
- Total 2400 aluminum bars

Results on monopole mass & charge from MMT 2012 run

First MoEDAL results!

JHEP 1608 (2016) 067 [arXiv:1604.06645]

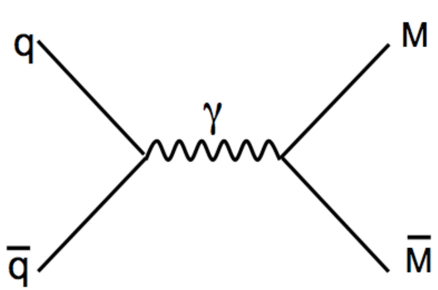
Magnetic monopoles

- 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

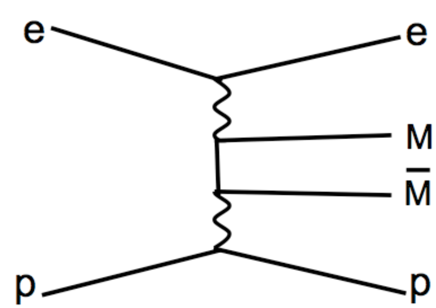
Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$
Gauss' law for magnetism:	$\vec{\nabla}\cdot\vec{B} = 0$	$\vec{\nabla}\cdot\vec{B} = 4\pi\rho_m$
Faraday's law of induction:	$-\vec{\nabla}\times\vec{E}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

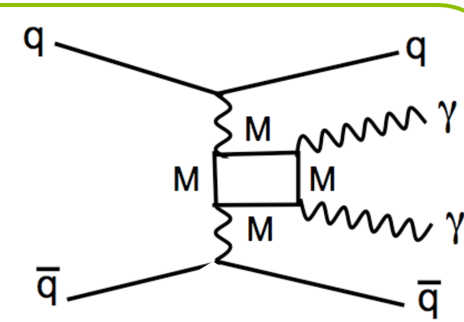
Production mechanisms in colliders



Drell Yan mechanism



Photon fusion

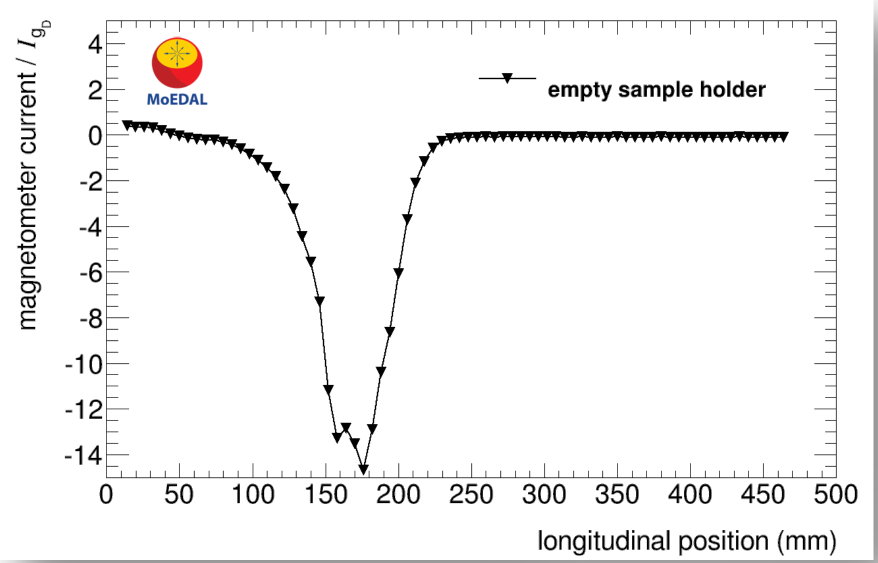


Box diagram

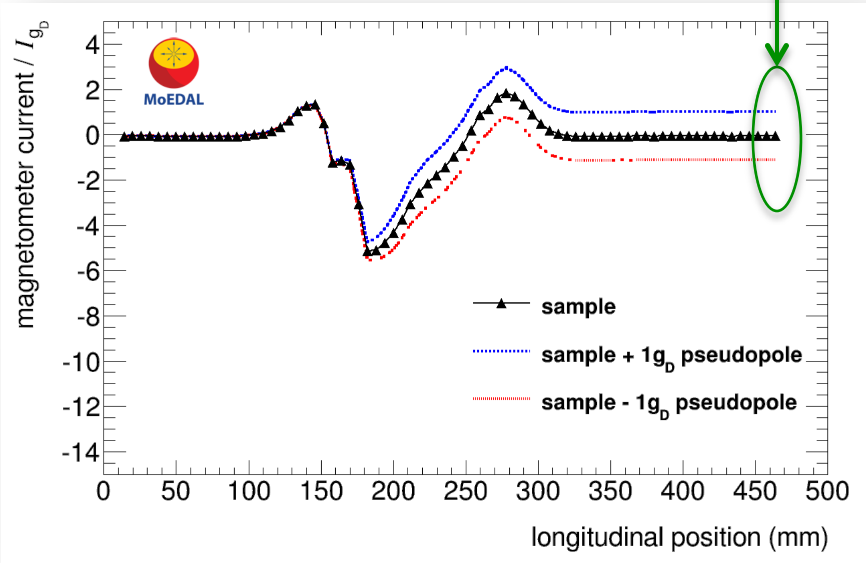
MoEDAL improves reach of monopole searches w.r.t. cross section & charge

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 & pseudo monopole curves

MMT 2012 analysis

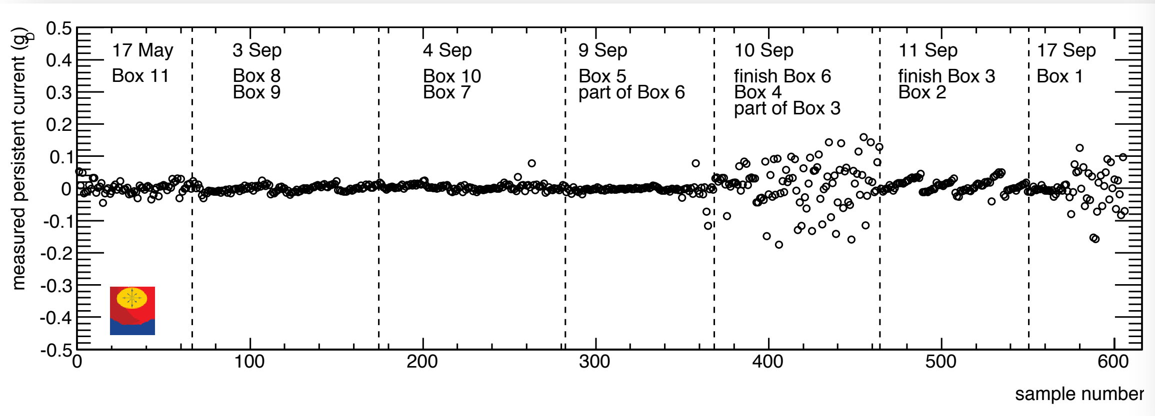
- Analysed with SQUID at ETH Zürich
- Excellent charge resolution (< 0.1 g_D) except for outliers
  - small occasional (2%) offset jumps due to known instrumental effects
  - multiple measurements of outliers yield currents consistent with zero

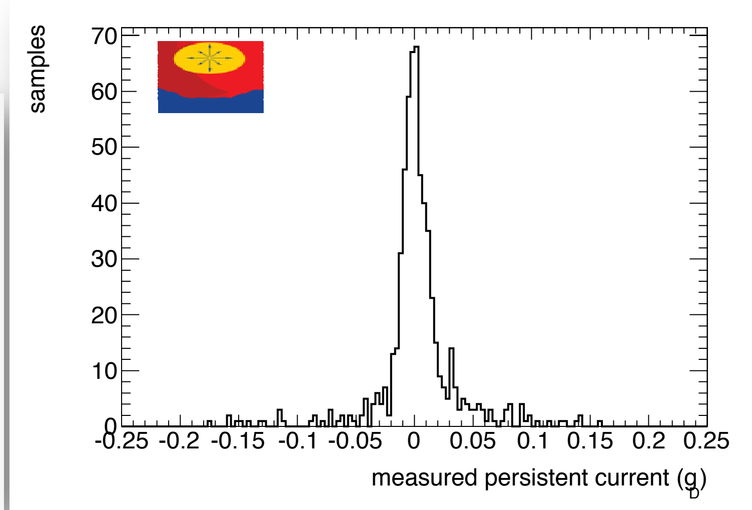
Detector: prototype of **160 kg** of Al rods

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

JHEP 1608 (2016) 067 [arXiv:1604.06645]

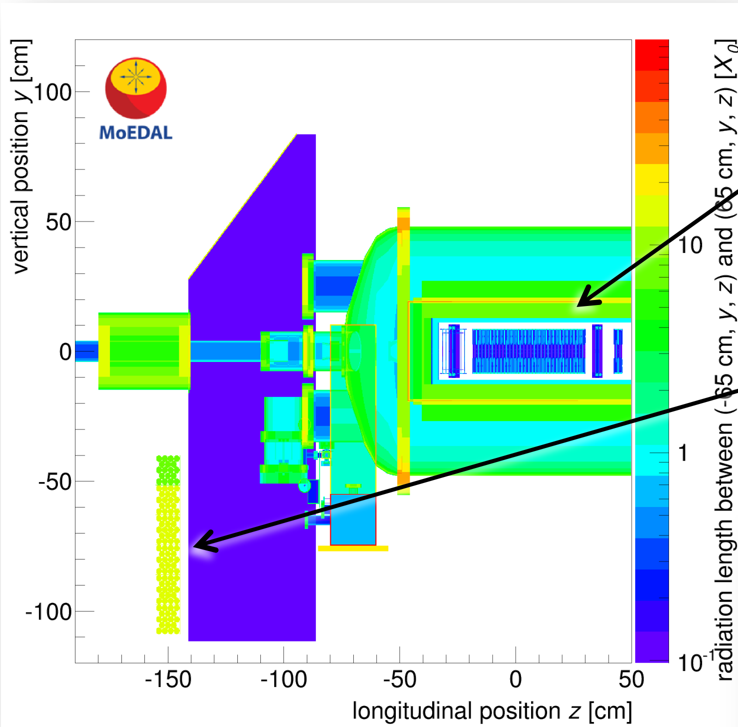
Persistent current after first passage for all samples





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

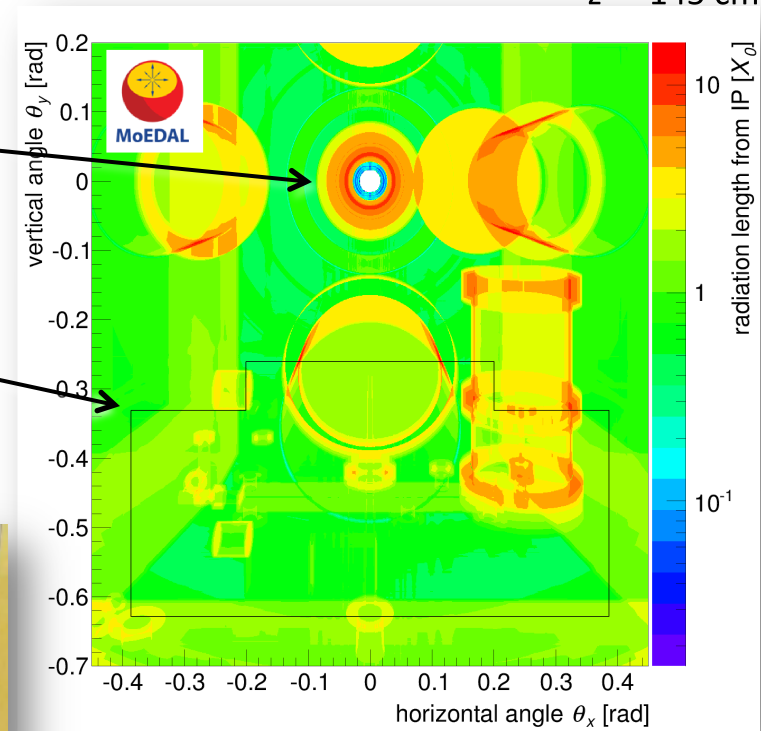
Geometry description



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

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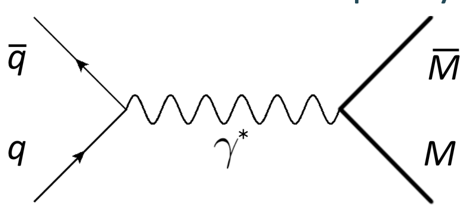
[arXiv:1604.06645]

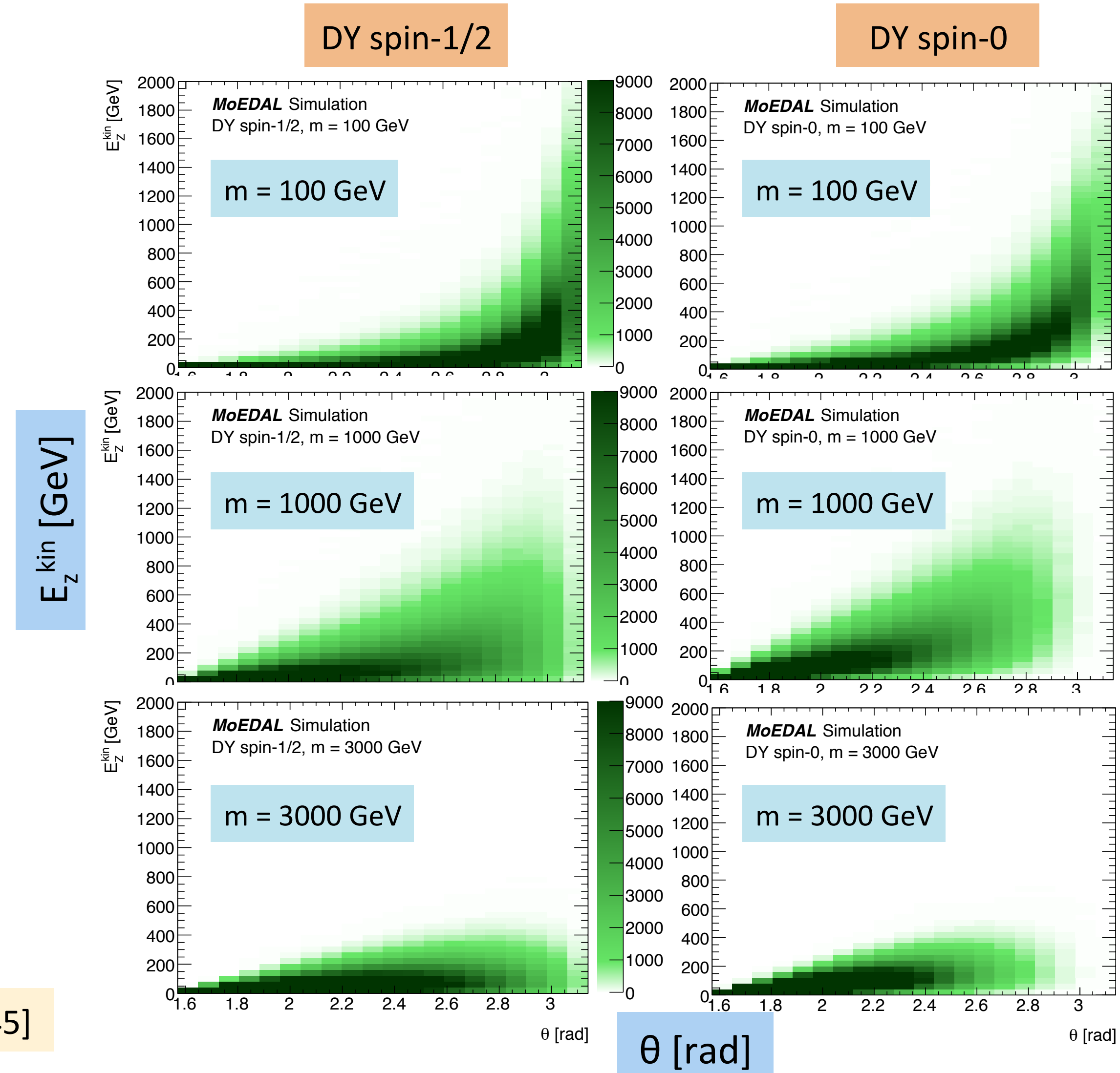
Monopole event generation

Two production processes

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



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



JHEP 1608 (2016) 067 [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 $\beta=10^{-2}$ limit
- Radiative effects significant only for $\beta\gamma > 70$ → neglected

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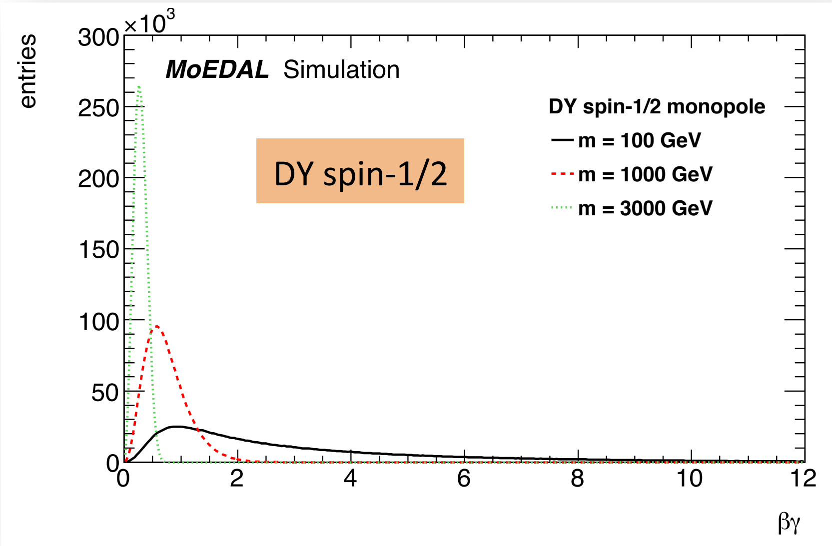

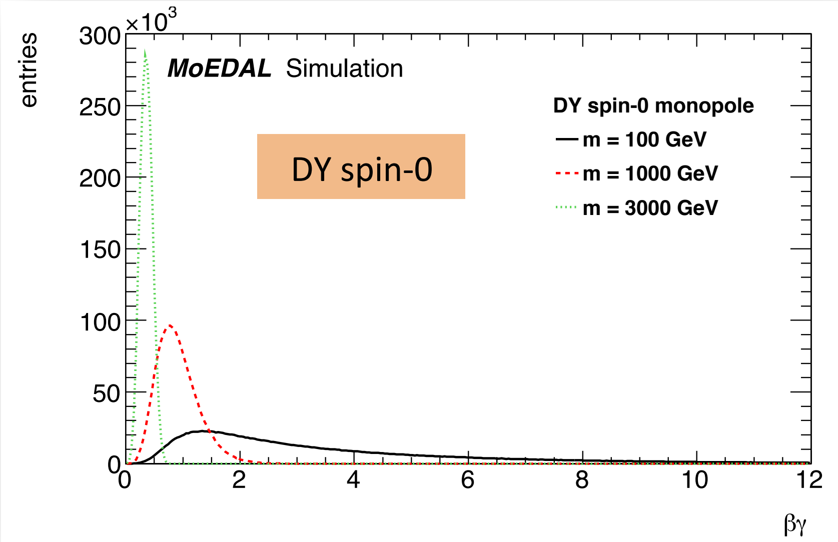

Trapping acceptance – Drell-Yan production

- 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

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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	—	—

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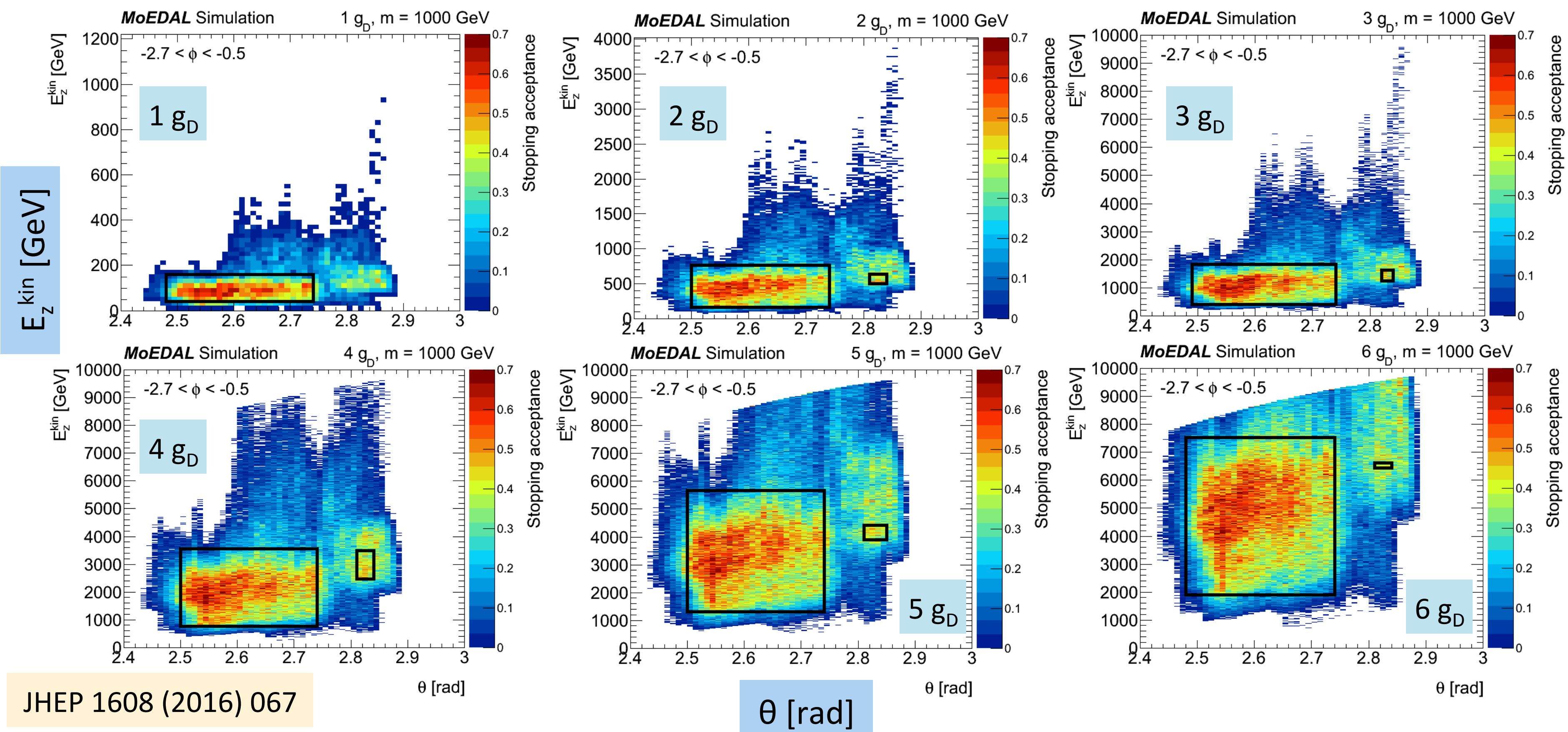
Trapping acceptance – model-independent

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



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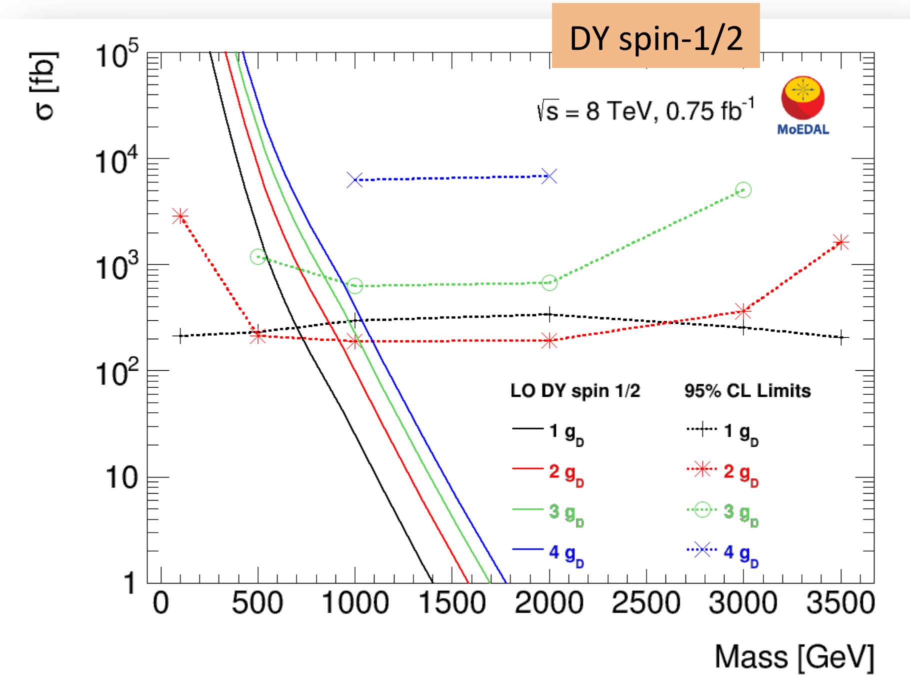
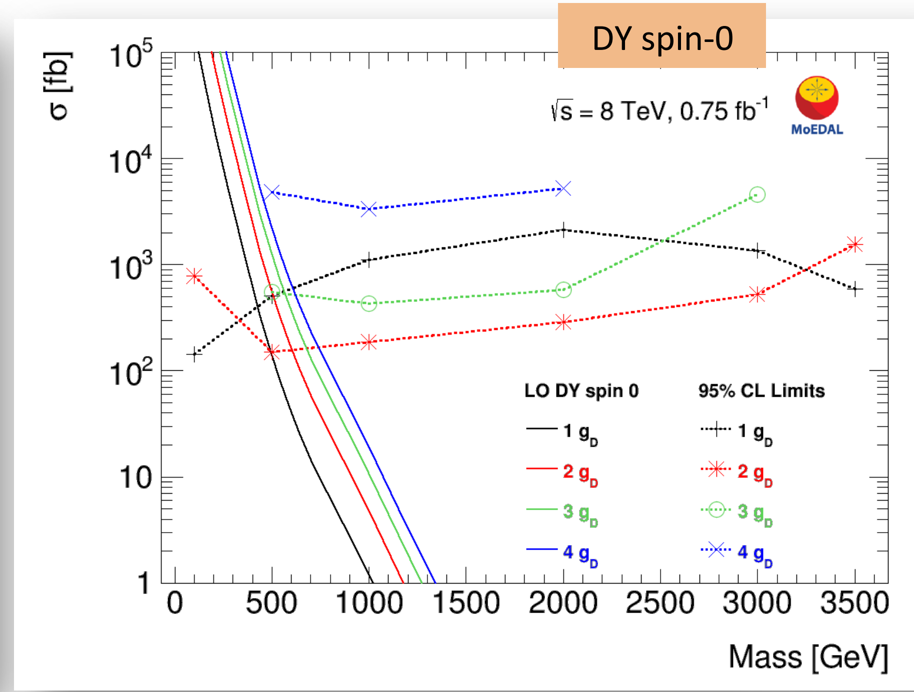
Cross section limits versus mass

DY spin-1/2



DY spin-0



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

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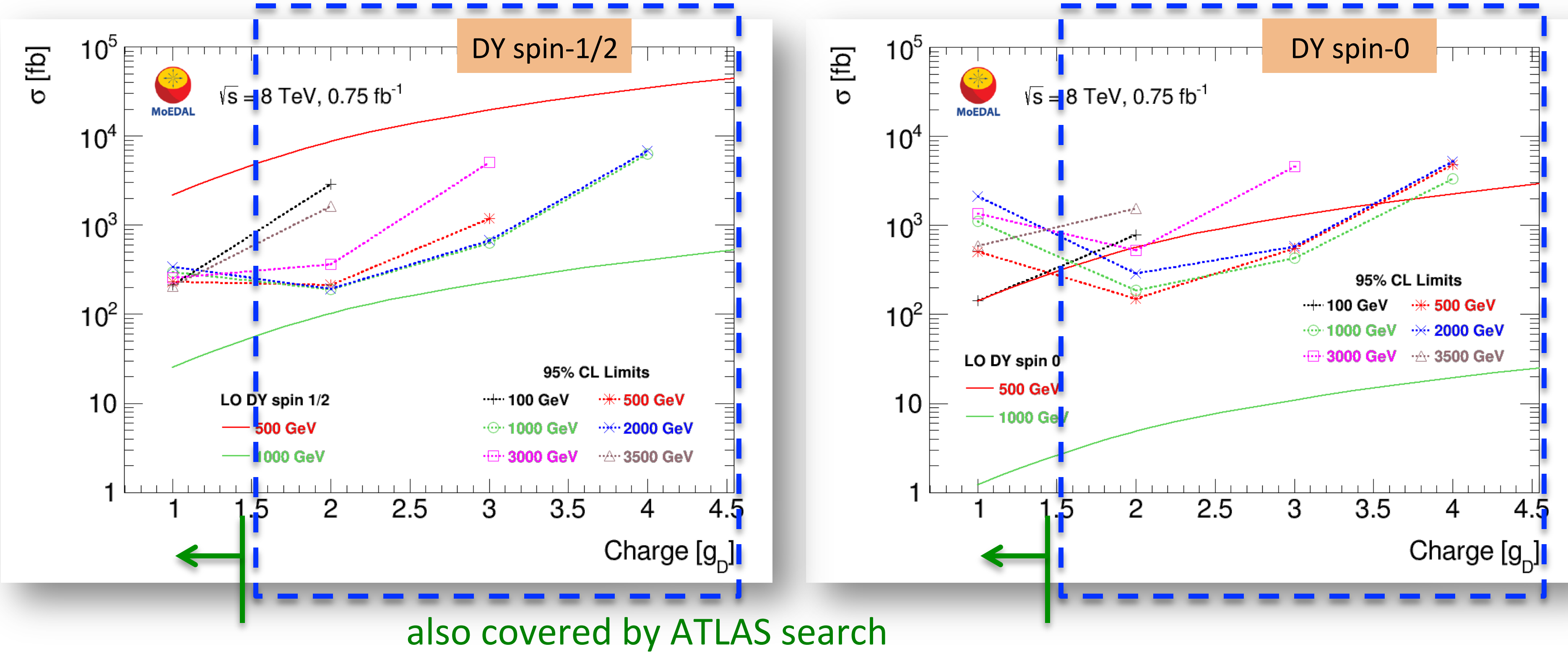
Cross section limits versus charge



Limits extend up to magnetic charge > 1.5g_D

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

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Mass & cross-section limits

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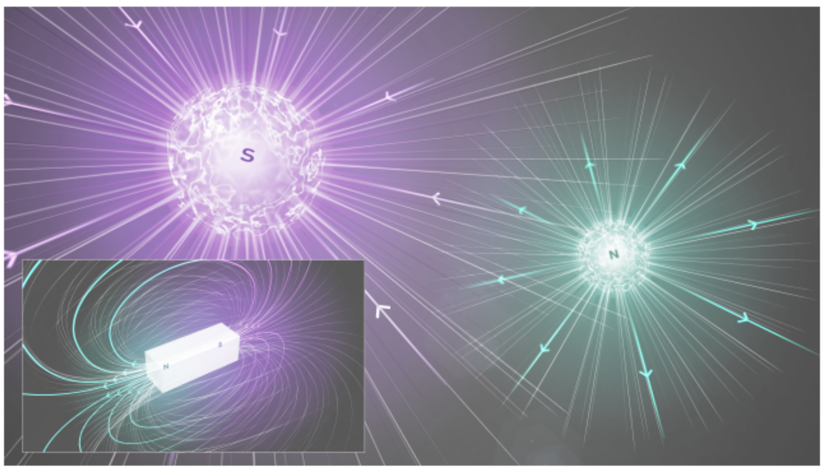
- Mass limits are *highly model-dependent*
  - Drell-Yan production does take into account non-perturbative nature of the large monopole-photon coupling

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 $6g_D$**

The LHC MoEDAL experiment publishes its first paper on its search for magnetic monopoles

10 Aug 2016



Magnetic monopoles and dipoles (Image: CERN)

Geneva, 10 August 2016. In a paper published by the journal JHEP today, the MoEDAL experiment at CERN[1] narrows the window of where to search for a hypothetical particle, the magnetic monopole. Over the last decades, experiments have been trying to find evidence for magnetic monopoles at accelerators, including at CERN's Large Hadron Collider. Such particles were first predicted by physicist Paul Dirac in the 1930s but have never been observed so far.

"Today MoEDAL celebrates the release of its first physics result and joins the other LHC experiments at the discovery frontier," says Spokesperson of the MoEDAL experiment, James Pinfold.

Just as electricity comes with two charges, positive and negative, so magnetism comes with two poles, North and

http://home.cern/about/updates/2016/08/moedal-closes-search-magnetic-particle

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

The MoEDAL collaboration

B. Acharya,[a,b] J. Alexandre,[a] K. Bendtz,[v,1] P. Benes,[k] J. Bernabéu,[c] M. Campbell,[da] S. Cecchini,[w] J. Chwastowski,[f] A. Chatterjee,[l] M. de Montigny,[g] D. Derendarz,[f] A. De Roeck,[da] J. R. Ellis,[a,db] M. Fairbairn,[a] D. Felea,[h] M. Frank,[ia] D. Frekers,[j] C. Garcia,[c] G. Giacomelli,[e,†] D. Haşegan,[ia] M. Kalliokoski,[dc] A. Katre,[l] D.-W. Kim,[m] M. G. L. King,[c] K. Kinoshita,[n] D.H. Lacarrère,[da] S. C. Lee,[m] C. Leroy,[ib] A. Lionti,[l] A. Margiotta,[e] N. Mauri,[w] N. E. Mavromatos,[a] P. Mermod,[l,2] D. Milstead,[v,1] V. A. Mitsou,[c] R. Orava,[o] B. Parker,[y] L. Pasqualini,[e] L. Patrizii,[w] G. E. Păvălaş,[h] J. L. Pinfold,[g] M. Platkevič,[k] V. Popa,[h] M. Pozzato,[w] S. Pospisil,[k] A. Rajantie,[p] Z. Sahnoun,[w,q] M. Sakellariadou,[a] S. Sarkar,[a] G. Semenoff,[r] G. Sirri,[w] K. Sliwa,[s] R. Soluk,[g] M. Spurio,[e] Y. N. Srivastava,[t] R. Staszewski,[f] M. Suk,[k] J. Swain,[t] M. Tenti,[z] V. Togo,[w] M. Trzebinski,[f] J. A. Tuszyński,[g] V. Vento,[c] O. Vives,[c] Z. Vykydal,[k] T. Whyntie,[y,z] A. Widom,[t] G. Willems[j] and J. H. Yoon[u]

[a] *Theoretical Particle Physics & Cosmology Group, Physics Dept., King's College London, U.K.*
[b] *International Centre for Theoretical Physics, Trieste, Italy*
[c] *IFIC, Universitat de València — CSIC, Valencia, Spain*
[da] *Experimental Physics Department, CERN, Geneva, Switzerland*
[db] *Theoretical Physics Department, CERN, Geneva, Switzerland*
[dc] *Beams Department, CERN, Geneva, Switzerland*
[e] *INFN, section of Bologna & Department of Physics & Astronomy, University of Bologna, Italy*
[f] *Institute of Nuclear Physics Polish Academy of Sciences, Cracow, Poland*
[g] *Physics Department, University of Alberta, Edmonton, Alberta, Canada*
[h] *Institute of Space Science, Bucharest — Măgurele, Romania*
[ia] *Department of Physics, Concordia University, Montréal, Québec, Canada*
[ib] *Département de physique, Université de Montréal, Québec, Canada*
[j] *Physics Department, University of Muenster, Muenster, Germany*
[k] *IEAP, Czech Technical University in Prague, Czech Republic*

[1] Associate member.
[†] Now deceased
[2] Corresponding author.

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Physics goals for MoEDAL

- beyond magnetic monopoles
- emphasis on supersymmetry

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

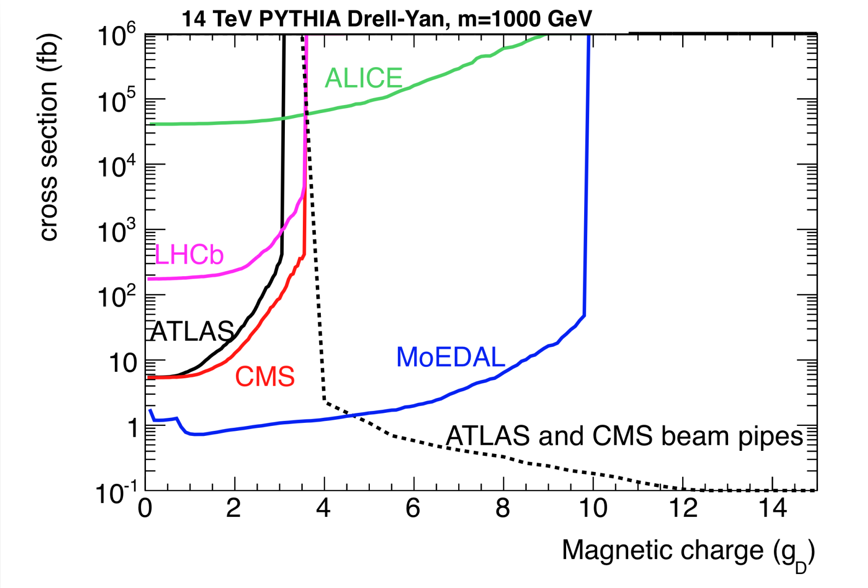
- MoEDAL is designed to detect charged particles, with effective or actual $z/\beta > 5$
- As it has no trigger/electronics slowly moving ($\beta <\ \sim 0.5$) particles are no problem
- One candidate event should be enough to establish a signal (no SM backgrounds)

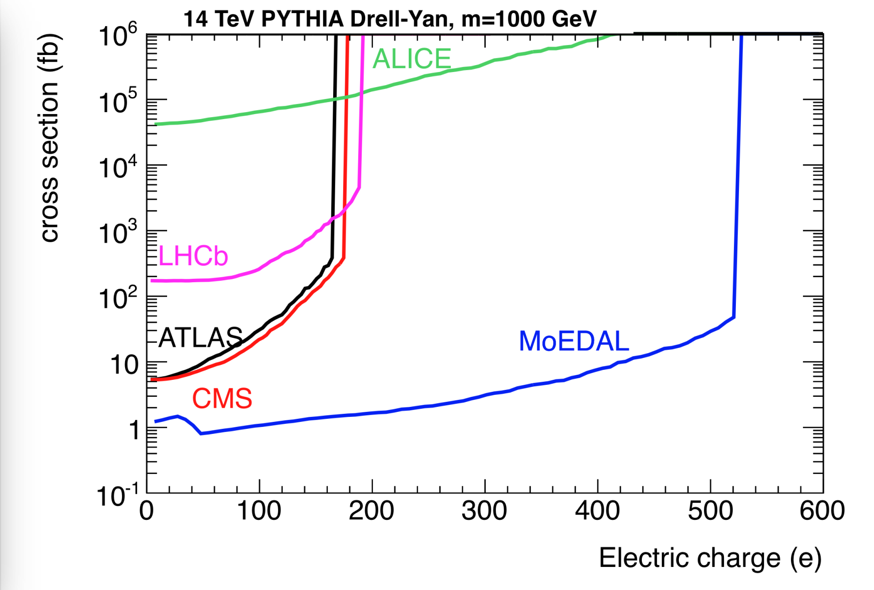
MoEDAL strengthens & expands the physics reach of LHC

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]

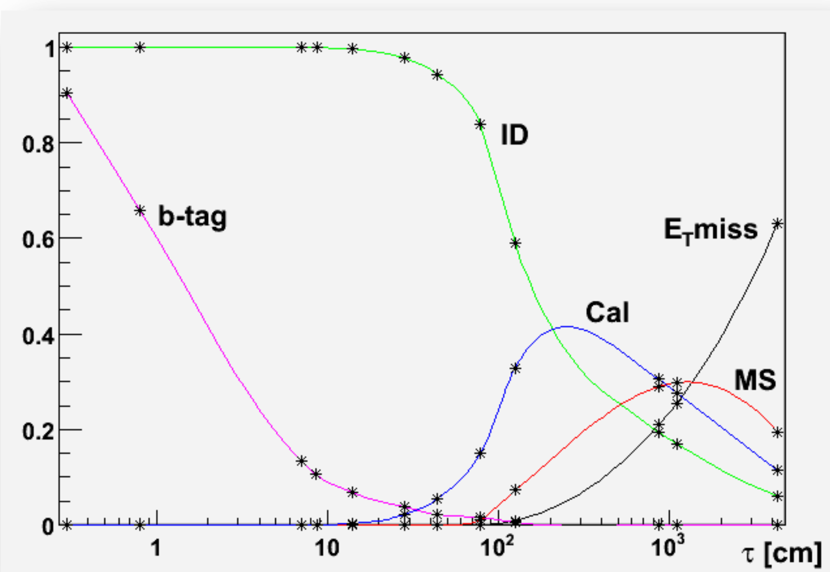
MoEDAL offers robustness against timing and well-estimated signal efficiency

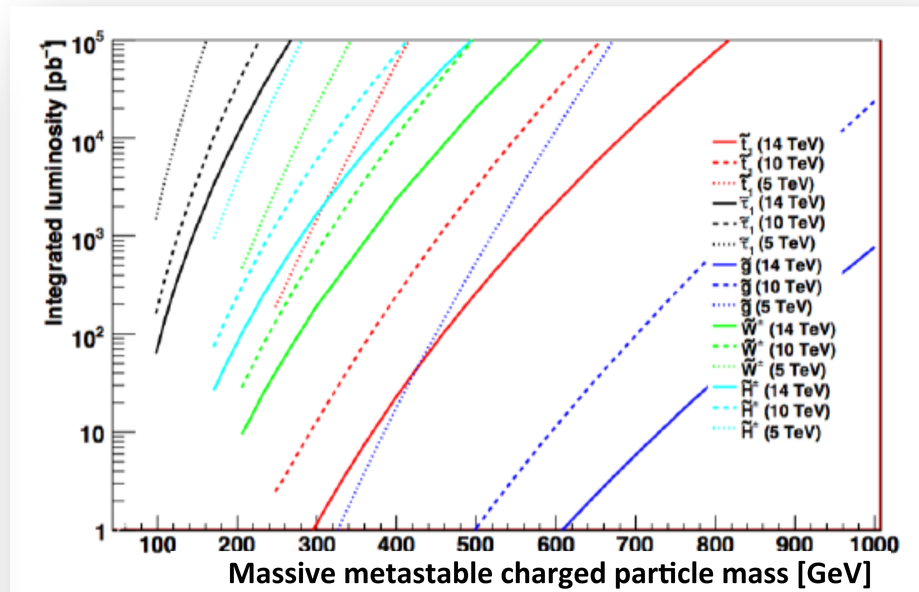
LHC sensitivity to sparticle direct production

- Metastable particles ≡ they live long enough to pass through detector
- Detection in ATLAS and CMS
  - large ionisation energy loss dE/dx, e.g. time-over-threshold in ATLAS Transition Radiation Tracker
  - nuclear interactions (R-hadron) in calorimeters
  - delay (time of flight) reconstructed in muon chambers

Integrated luminosities needed for discovery at LHC at 14 TeV (solid), 10 TeV (dashed) and 5 TeV (dotted)

- signal efficiency of 20% (5%) for electrically charged (strongly interacting) SMCPs
- 1 bkg event for 100 pb^{-1}

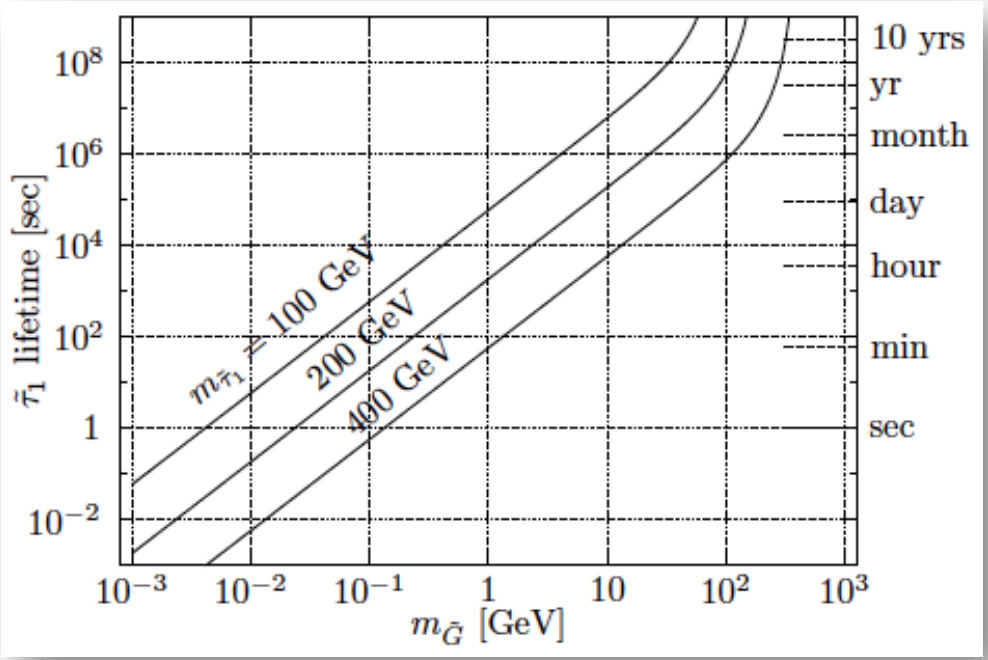




Raklev, Mod.Phys.Lett. A24 (2009) 1955

Long-lived sleptons – GMSB

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



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

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

average distance travelled

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

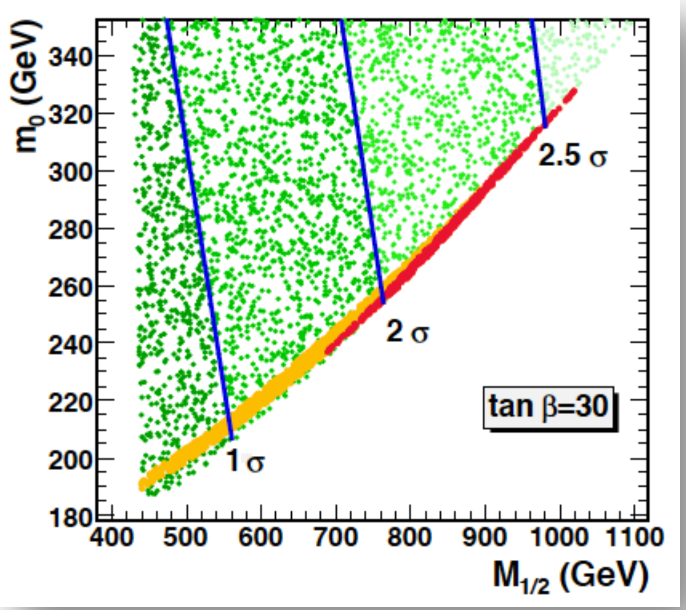
Long-lived sleptons – CMSSM

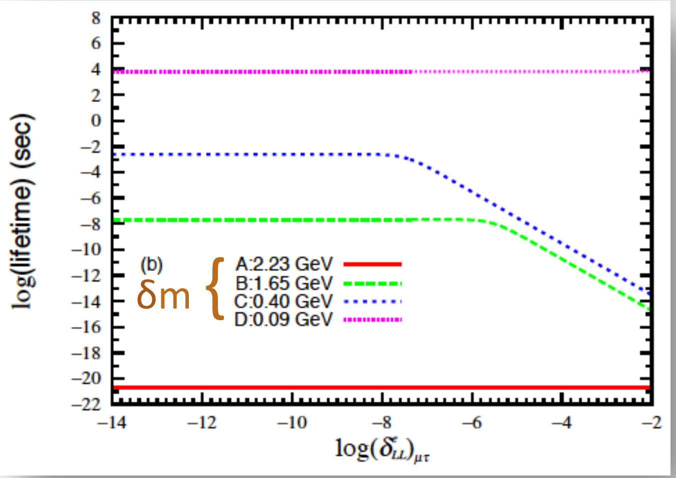
- Stau becomes long lived in MSSM when $m(\tilde{\tau}) - m(\tilde{\chi}_1^0) < m(\tau)$
- Coannihilation region in CMSSM
- Consistent with cosmological constraints
- Lepton Flavour Violating (LFV) elements in slepton mass matrix may decrease stau lifetime

$$(\delta^e_{RR/LL})_{\alpha\beta} = \frac{\Delta M^{e\ 2}_{RR/LL_{\alpha\beta}}}{M^e_{R/L\alpha} M^e_{R/L\beta}},$$

- Stau remains metastable in large regions of parameter space

$$\Gamma_{2-\text{body}} = \frac{g_2^2}{2\pi m_{\tilde{\tau}_1}} (\delta m)^2 (|g^L_{1\alpha 1}|^2 + |g^R_{1\alpha 1}|^2),$$





Kaneko, Sato, Shimomura, Vives, Yamanaka, PRD87 (2013) 039904 [arXiv:0811.0703]

R-hadrons

- Gluinos in Split Supersymmetry
  - long-lived because squarks very heavy
  - possible gluino hadrons: $R = \tilde{g}q\bar{q},\ \tilde{g}qqq,\ \tilde{g}g$
  - gluino hadrons may flip charge as they pass through matter
    - e.g., $\tilde{g}u\bar{u}$ + uud → $\tilde{g}$ud + u$\bar{u}$
    - ☛ may be missed by ATLAS and CMS

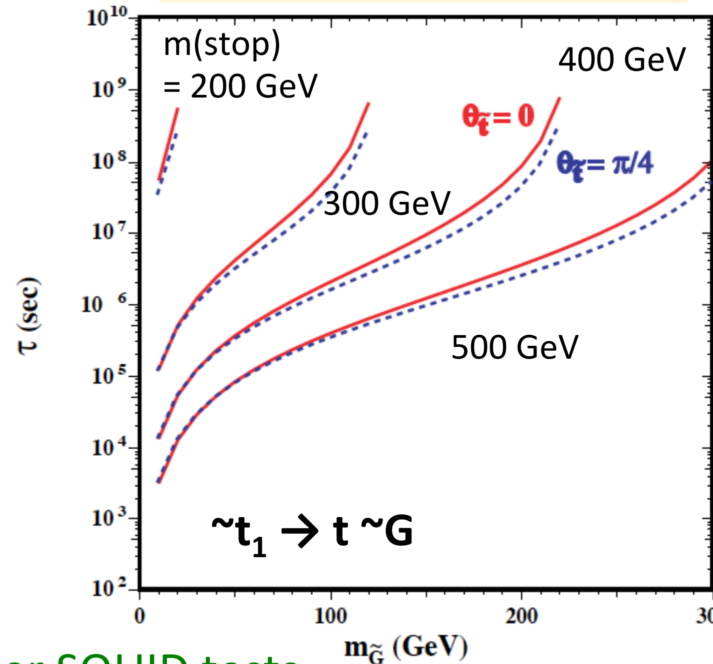
$$\tau \simeq 8 \left(\frac{m_S}{10^9\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \mathrm{s}$$

- *R*-parity violating SUSY

$$W_{RV} = \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \lambda_{ijk}L_iL_j\bar{E}_k + \mu_i L_i H,$$

  - if λ' or λ''≠0, stop NLSP case → stop R-hadron → metastable charged particle in material → detection in MoEDAL, if sufficiently slow

Diaz-Cruz et al, JHEP 0705 (2007) 003



- Moreover R-hadrons may be "trapped" in MMTs and decay at later times ➜ monitoring of MMTs after SQUID tests

Why MoEDAL when searching SMCPs?

- ATLAS and CMS triggers have to
  - rely on other "objects", e.g. E_T^{miss}, that accompany SMCPs, thus limiting the reach of the search
    - final states with associated object present
    - trigger threshold set high for high luminosity
  - develop specialised triggers
    - dedicated studies needed
    - usually efficiency significantly less than 100%
- Timing: signal from (slow-moving) SMCP should arrive within the correct bunch crossing
- MoEDAL mainly constrained by its geometrical acceptance
- When looking for trapped particles
  - monitoring of detector volumes in an underground laboratory has less background than using empty butches in LHC cavern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The physics programme of the MoEDAL experiment at the LHC

B. Acharya,[1,2] J. Alexandre,[1] J. Bernabéu,[3] M. Campbell,[4] S. Cecchini,[5]
J. Chwastowski,[8] M. De Montigny,[9] D. Derendarz,[8] A. De Roeck,[4] J. R. Ellis,[1,4]
M. Fairbairn,[1] D. Felea,[10] M. Frank,[11] D. Frekers,[12] C. Garcia,[3] G. Giacomelli,[5,6,*]
J. Jakůbek,[13] A. Katre,[14] D.-W. Kim,[15] M. G. L. King,[3] K. Kinoshita,[16]
D. Lacarrere,[4] S. C. Lee,[15] C. Leroy,[17] A. Margiotta,[5] N. Mauri,[5,6]
N. E. Mavromatos,[1,4] P. Mermod,[14] V. A. Mitsou,[3] R. Orava,[18] L. Pasqualini,[5,6]
L. Patrizii,[5] G. E. Păvălaş,[10] J. L. Pinfold,[9,†] M. Platkevič,[13] V. Popa,[10]
M. Pozzato,[5] S. Pospisil,[13] A. Rajantie,[19] Z. Sahnoun,[5,7] M. Sakellariadou,[1]
S. Sarkar,[1] G. Semenoff,[20] G. Sirri,[5] K. Sliwa,[21] R. Soluk,[9]
M. Spurio,[5,6] Y. N. Srivastava,[22] R. Staszewski,[8] J. Swain,[22] M. Tenti,[5,6]
V. Togo,[5] M. Trzebinski,[8] J. A. Tuszyński,[9] V. Vento,[3] O. Vives,[3]
Z. Vykydal,[13] A. Widom[22] and J. H. Yoon[23]

(for the MoEDAL Collaboration)

[1] *Theoretical Particle Physics and Cosmology Group, Physics Department, King's College London, UK*
[2] *International Centre for Theoretical Physics, Trieste, Italy*
[3] *IFIC, Universitat de València - CSIC, Valencia, Spain*
[4] *Physics Department, CERN, Geneva, Switzerland*
[5] *INFN, Section of Bologna, 40127, Bologna, Italy*
[6] *Department of Physics & Astronomy, University of Bologna, Italy*
[7] *Centre on Astronomy, Astrophysics and Geophysics, Algiers, Algeria*
[8] *Institute of Nuclear Physics Polish Academy of Sciences, Cracow, Poland*
[9] *Physics Department, University of Alberta, Edmonton Alberta, Canada*
[10] *Institute of Space Science, Măgurele, Romania*
[11] *Department of Physics, Concordia University, Montreal, Quebec, Canada*
[12] *Physics Department, University of Muenster, Muenster, Germany*
[13] *IEAP, Czech Technical University in Prague, Czech Republic*
[14] *Section de Physique, Université de Genève, Switzerland*
[15] *Physics Department, Gangneung-Wonju National University, Gangneung, Korea*
[16] *Physics Department, University of Cincinnati, Cincinnati OH, USA*
[17] *Physics Department, Université de Montréal, Montréal, Québec, Canada*
[18] *Physics Department, University of Helsinki, Helsinki, Finland*
[19] *Physics Department, Imperial College London, UK*
[20] *Department of Physics, University of British Columbia, Vancouver BC, Canada*
[21] *Department of Physics and Astronomy, Tufts University, Medford MA, USA*
[22] *Department of Physics, Northeastern University, Boston, USA*
[23] *Physics Department, Konkuk University, Seoul, Korea*
[†] *jpinfold@ualberta.ca*

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:

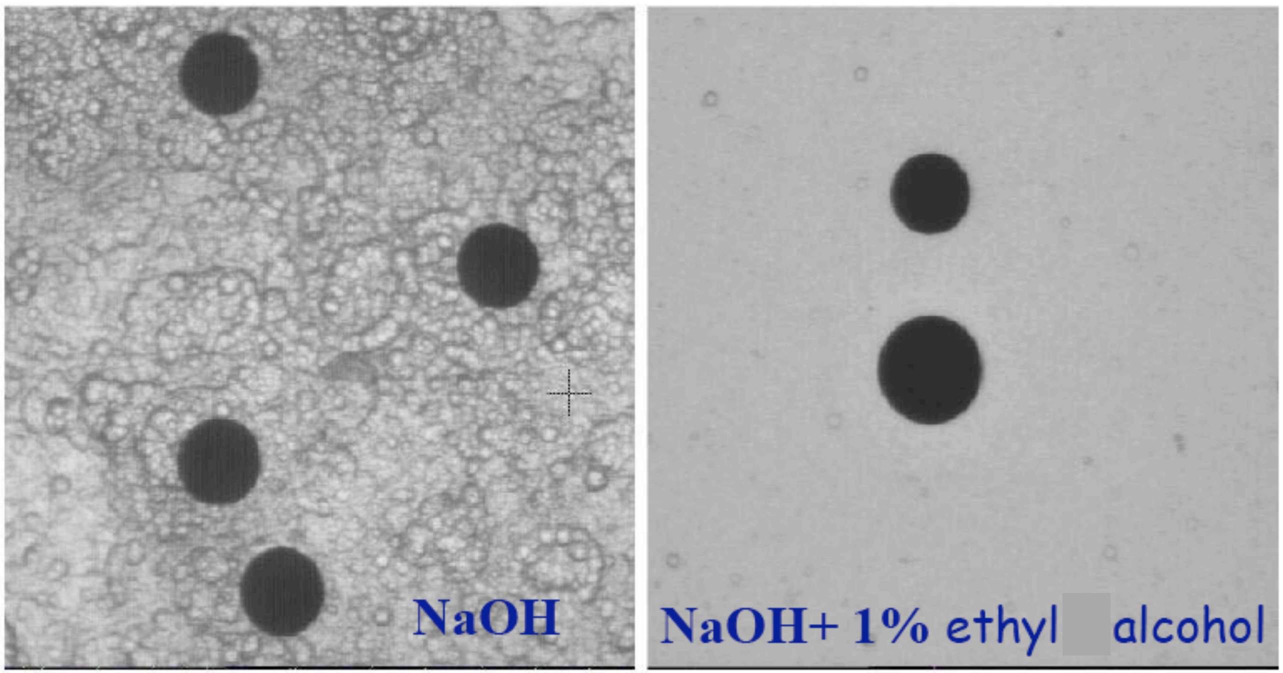
http://moedal.web.cern.ch/

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 published in JHEP
- Looking forward to many more results from Run-II and beyond
  - for other monopole production processes
  - with NTDs
  - for electrically-charged particles

Spares

NTD scanning results

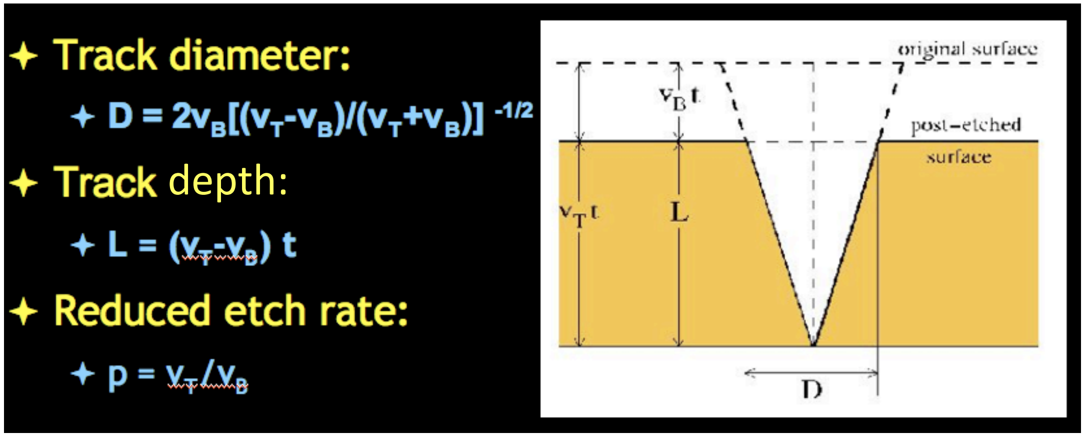


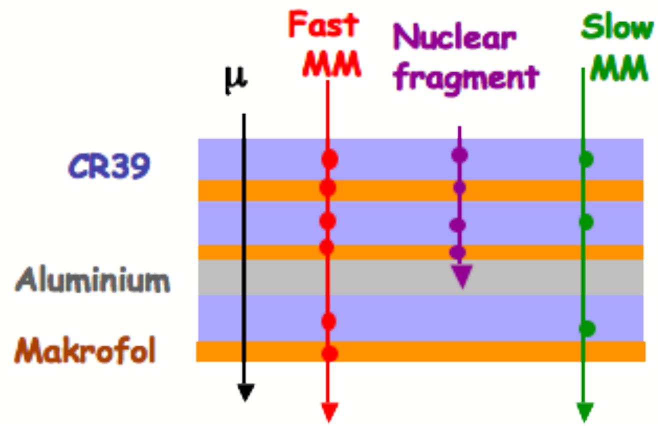
(a) Makrofol etched in 6N NaOH at 50 C for 95 hours

(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





- 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* $REL = (dE/dx)_{10\text{nm from track}}$

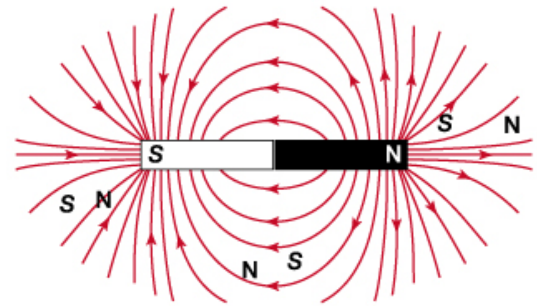
Dirac's Monopole

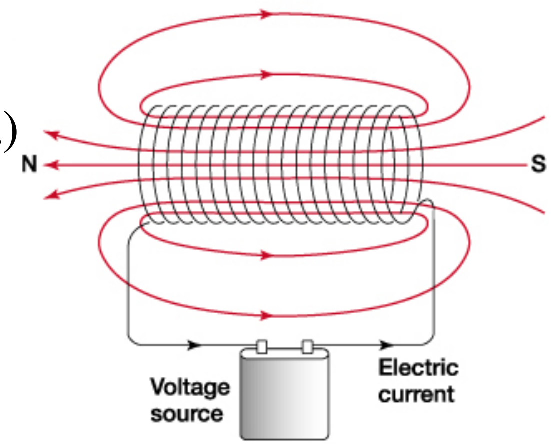
- Paul Dirac in 1931 hypothesized that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac's quantisation condition:

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

- 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:

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

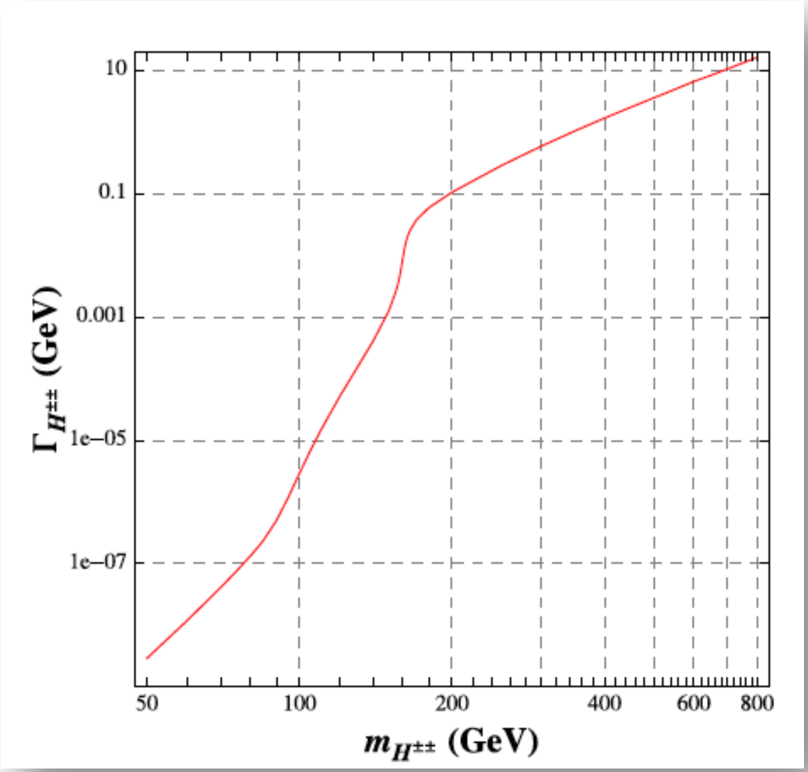




Dirac String

Doubly-charged Higgs

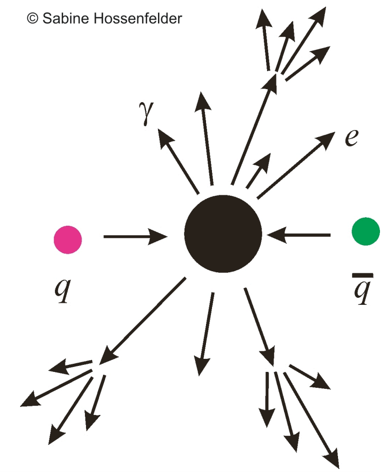
- Extended Higgs sector in BSM models: $SU_L(2) \times SU_R(2) \times U_{B-L}(1)$ P-violating model
- Higgs triplet model with massive left-handed neutrinos but not right-handed ones
- Common feature: **doubly charged Higgs bosons $H^{\pm\pm}$** as parts of a Higgs triplet
- Lifetime
  - depends on many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



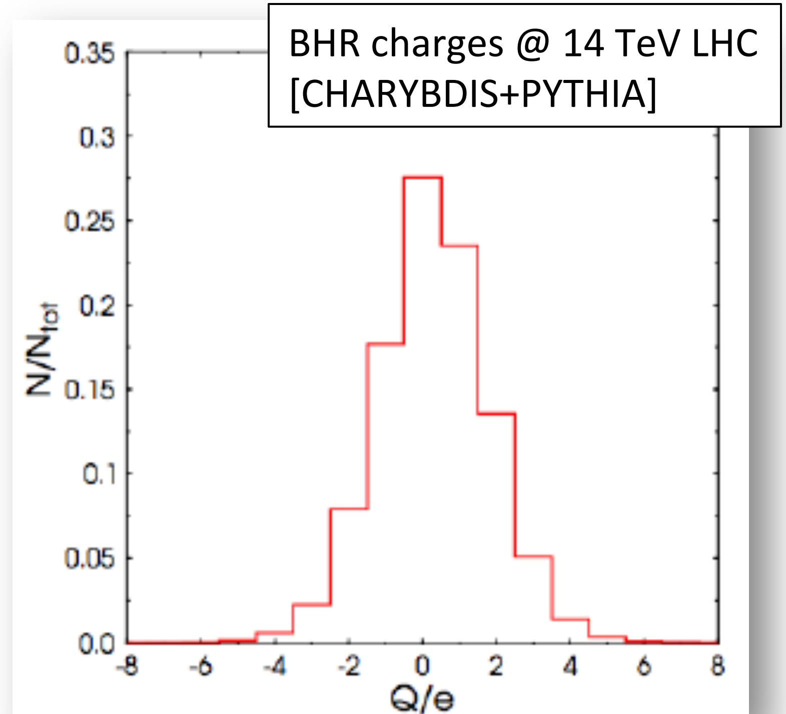
Partial decay width of $H^{\pm\pm} \to W^{\pm}W^{\pm}$

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

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