Magnetic monopole searches with the MoEDAL experiment at the LHC

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On behalf of the MoEDAL collaboration
EPS-HEP Conference
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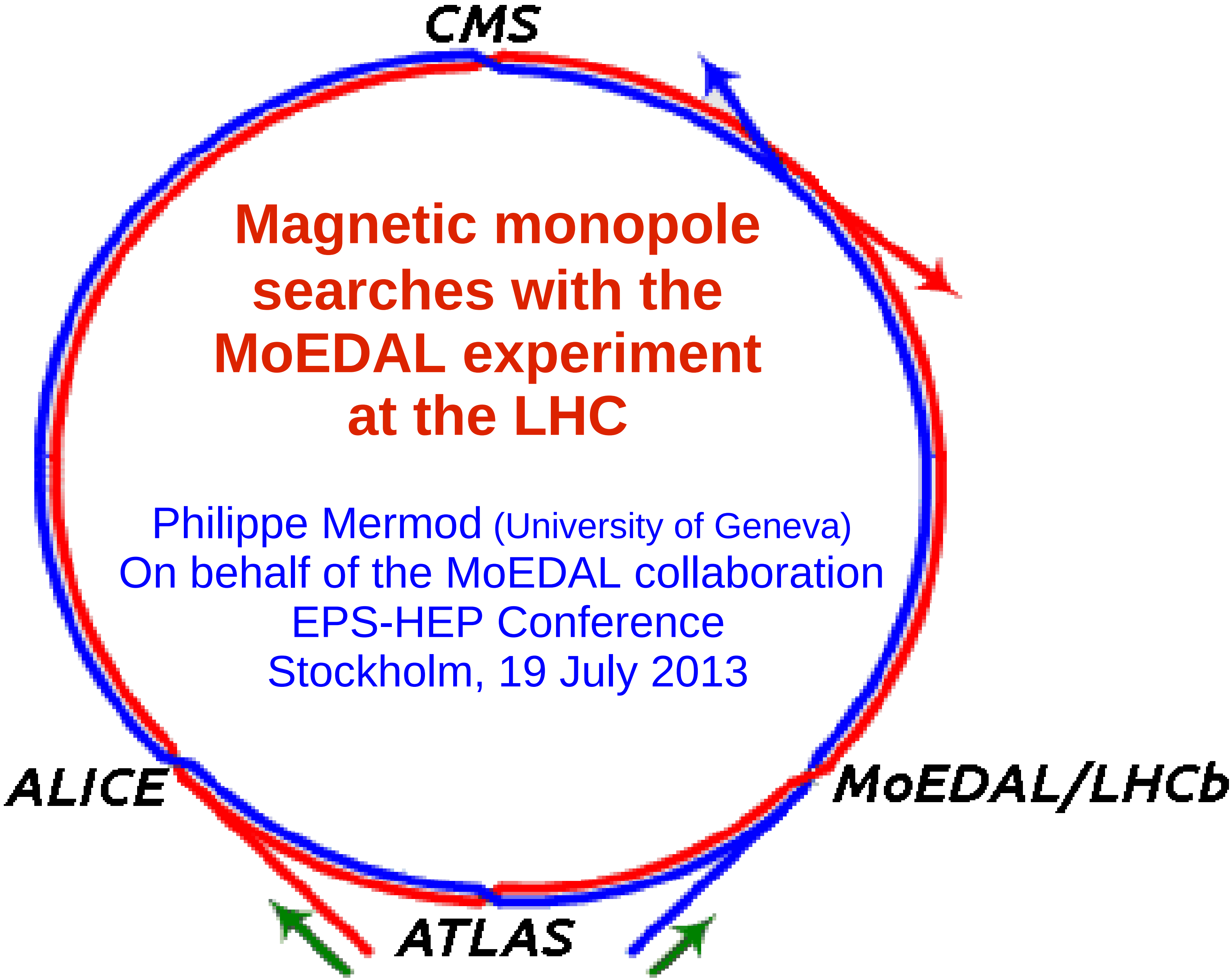
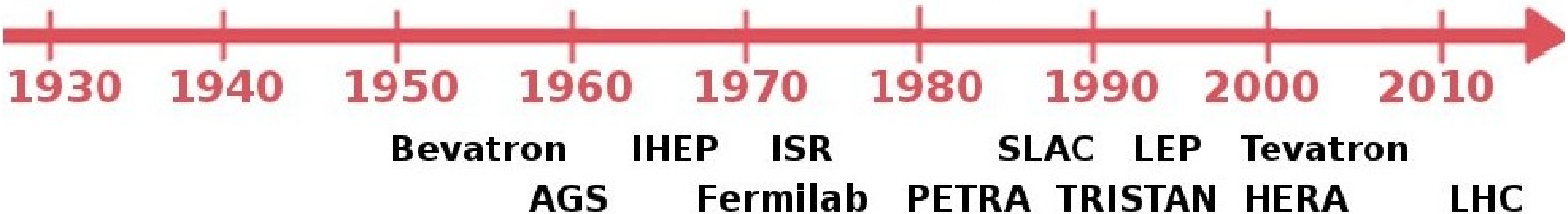


Magnetic monopoles

- Dirac argument (1931): existence of magnetic charge would explain electric charge quantisation
  - Basic unit of magnetic charge: $g_D = 68.5e$
  - Monopoles should carry *a multiple* of g_D : $g = Ng_D$
  - $2Ng_D$ according to Schwinger's argument (1966)
  - $3Ng_D$ if basic electric charge is *e/3* (quark charge)
- Coupling to the photon $\gg 1$
  - Non-perturbative dynamics
  - Very large ionisation energy loss
- Magnetic charge conservation ensures that monopoles would be stable and produced in pairs

Monopole searches

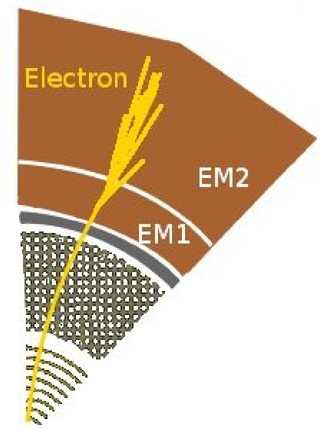
- In cosmic rays (e.g. MACRO detector array)
- In matter (e.g. polar volcanic rocks, see previous talk)
- At colliders (each time a new energy regime is reached)

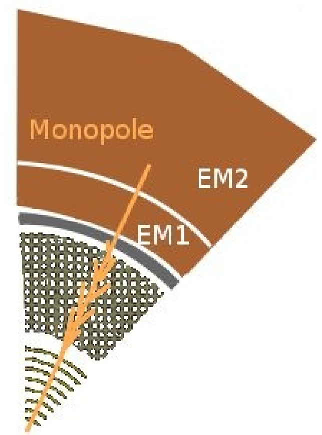


Monopole searches at the LHC

- ATLAS set the first limits on monopole production at the LHC
  - 2 fb^{-1} of 7 TeV *pp* collision data
  - Cross section limits *for* $g = g_D$ and 200 < mass < 1500 GeV

  (PRL 109, 261803 (2012), arXiv:1207.6411)





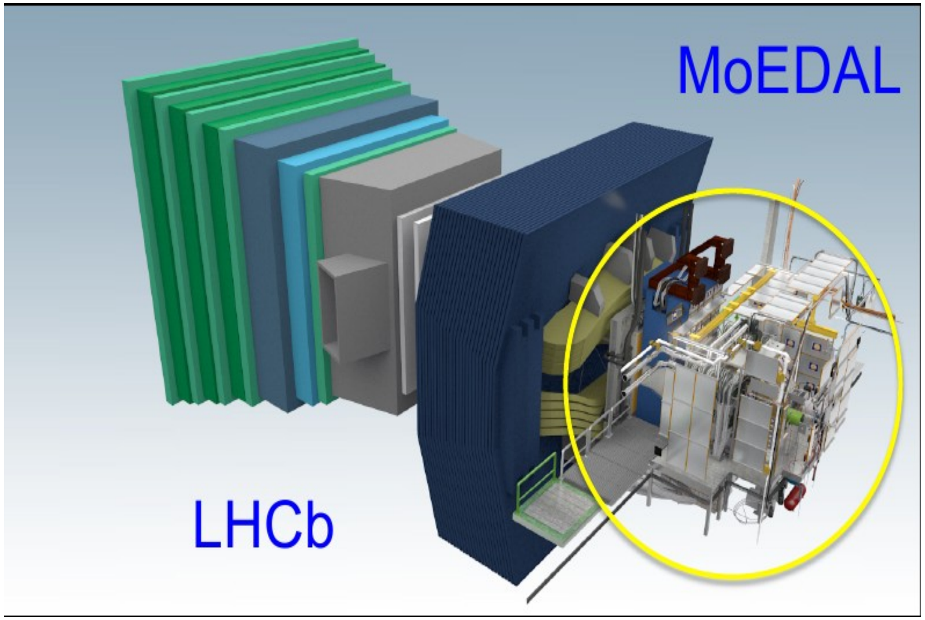
- 8 TeV collision data collected in 2012:
  - ATLAS and CMS → $g \leq 2g_D$
  - MoEDAL test arrays → $g \leq 6g_D$
  - Monopoles trapped in ATLAS and CMS beam pipes → $g \geq 4g_D$
  - Complementary techniques!

The MoEDAL experiment

- International collaboration of 42 members from 19 institutes

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

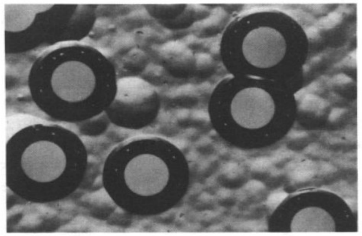
- Dedicated to highly-ionising particle detection
  - Magnetic monopoles and other long-lived massive charged particles
  - Sensitivity surpasses other LHC experiments in many cases + complementary



- Design consists of 4 detector subsystems
  - The TDR Nuclear Track detector (NTD) array ($Z \geq 5$)
  - The Very High Charge Catcher (VHCC) NTD array ($Z \geq 50$)
  - The Magnetic Monopole Trapper (MMT) absorbing array
  - The TimePix chip (TMPX) online radiation monitoring system

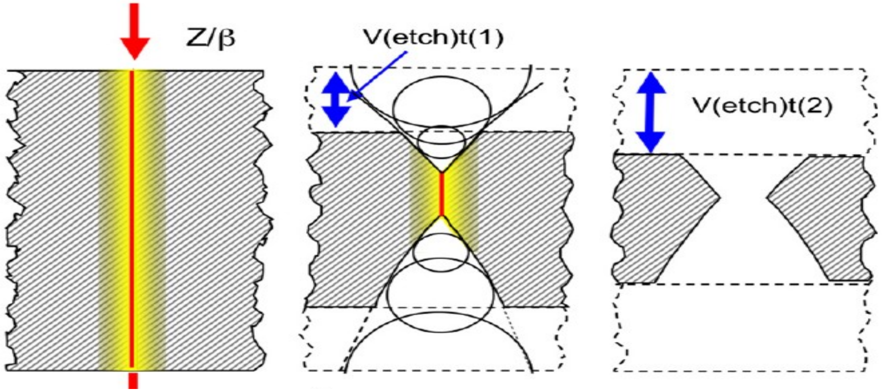
MoEDAL detection principles

Passive detector arrays exposed to collision products around LHC interaction point-8



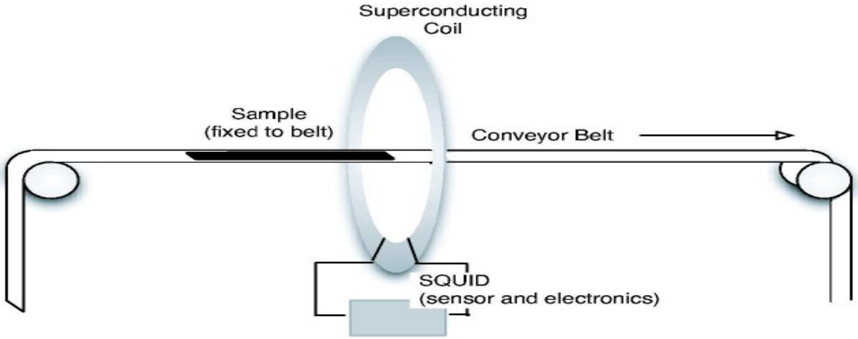
Nuclear track detectors (NTDs)**:**

- Thin plastic foils
- Track-etch technique for signature of high ionisation



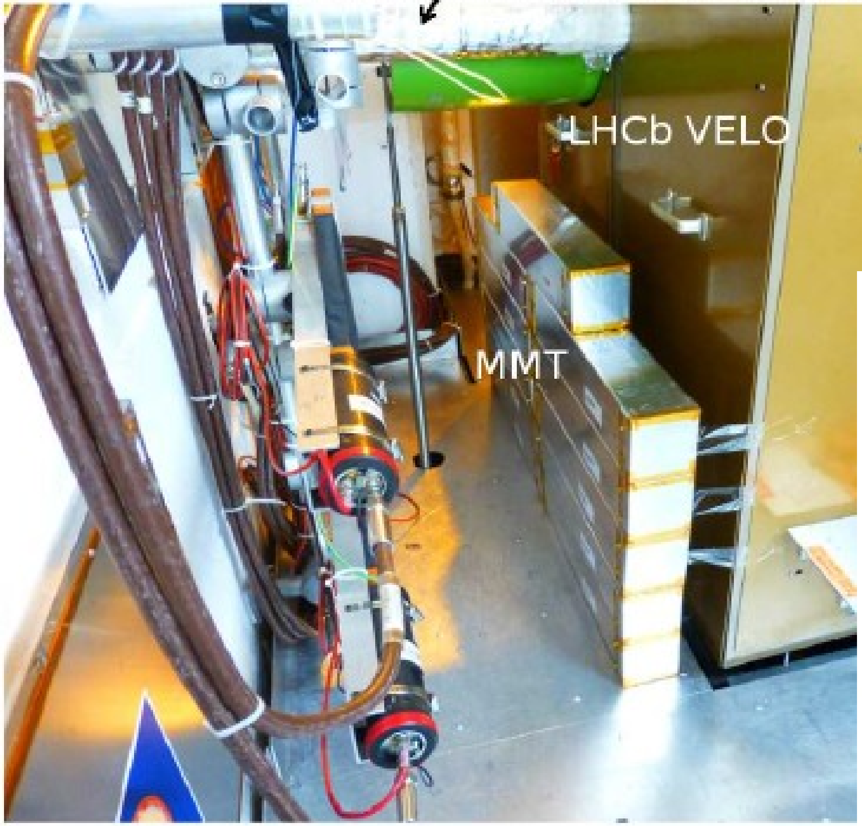
Magnetic monopole trapper (MMT)**:**

- Aluminium absorber
- Induction technique for signature of magnetic pole



MoEDAL arrays

LHC beam pipe; interaction point → (x)



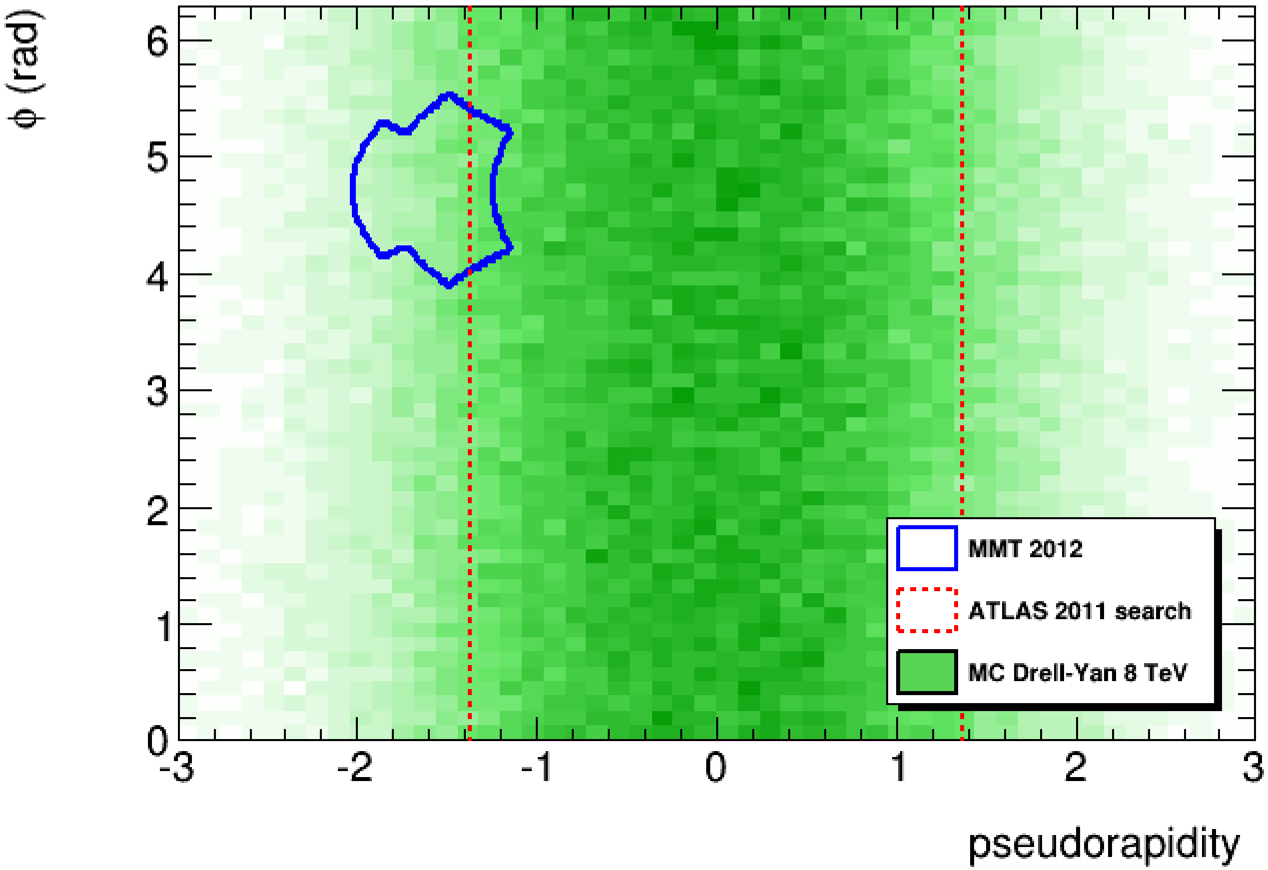
Test arrays deployed in 2012 (8 TeV)

→ NTD and MMT exposure, first MMT data shown today

Final arrays to be deployed in 2015-2016 (14 TeV)

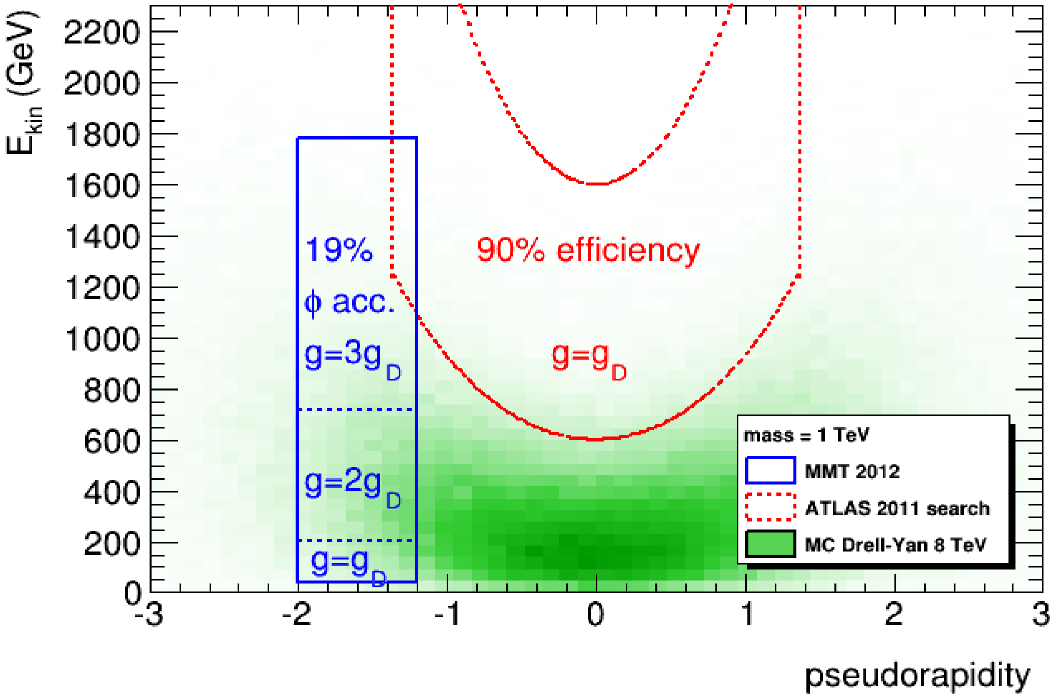
MMT 2012 – geometrical acceptance

Array placed 1.8 m away from the interaction point, covers 1.3 % of the total solid angle



MMT 2012 – kinematic acceptance

Relatively low material budget in front of the MMT (~ 14 g·cm^{-2})



→ probe yet unexplored kinematic ranges:

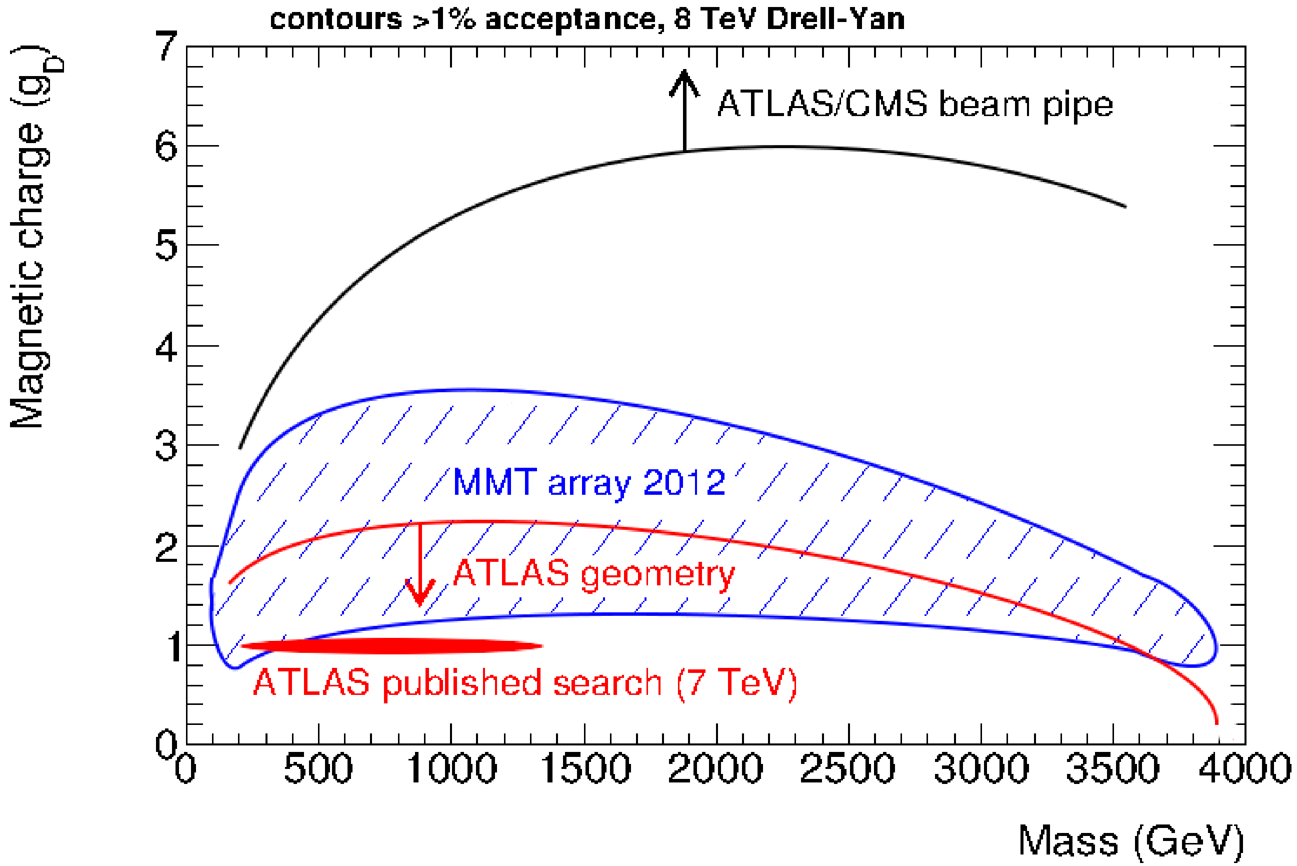
- Low energies
- Forward region

Important to cover wide energy and angular ranges due to large model uncertainties

MMT 2012 – probed parameter space

Charge > $1g_D$ and mass > 1500 GeV still unconstrained in LHC energy regime...

This is now being remedied!



Calculations methods described in EPJC 72, 1985 (2012), arXiv:1112.2999

Magnetometer measurements

Laboratory of Natural Magnetism, ETH Zurich

Magnetically shielded room

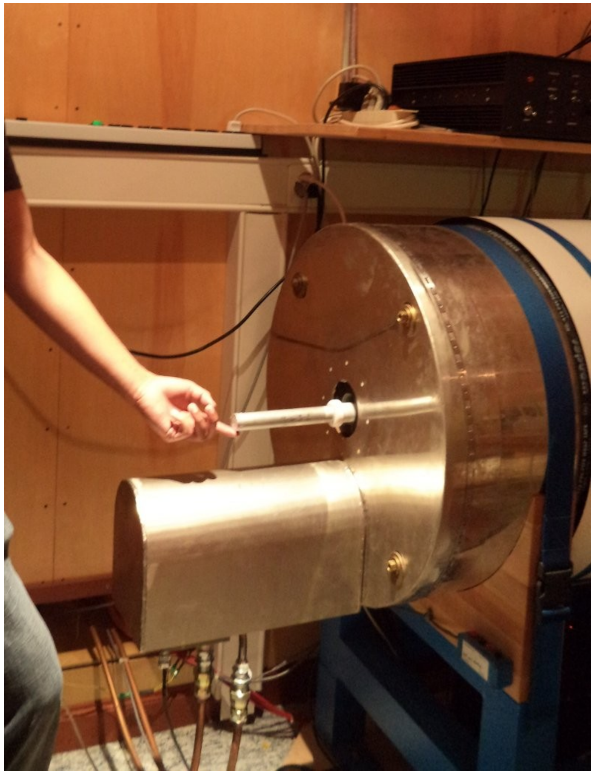
DC-SQUID magnetometer

For details about the method and calibration, see previous talk by D. Milstead

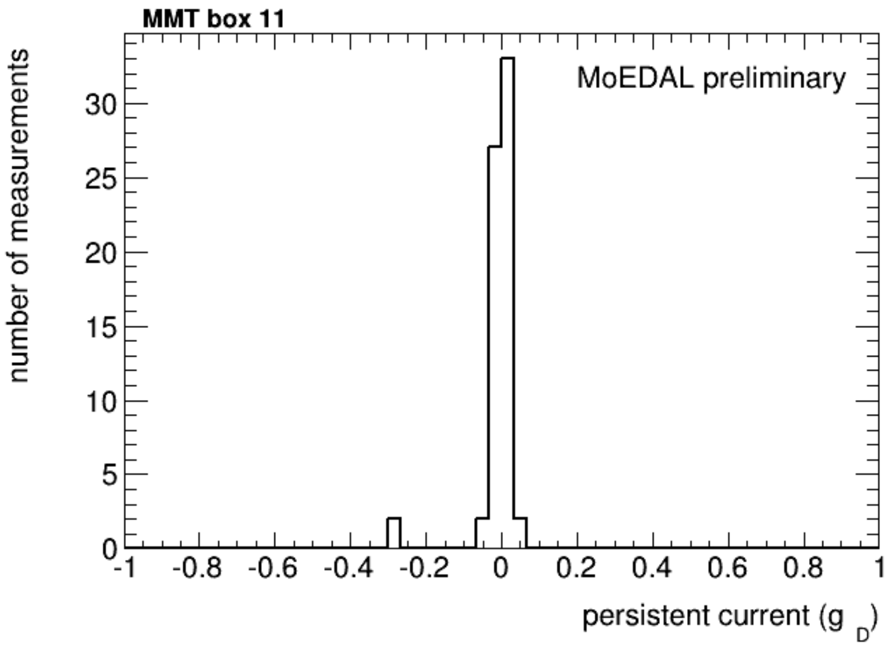
(see also EPJC 72, 2212 (2012), arXiv:1206.6793)

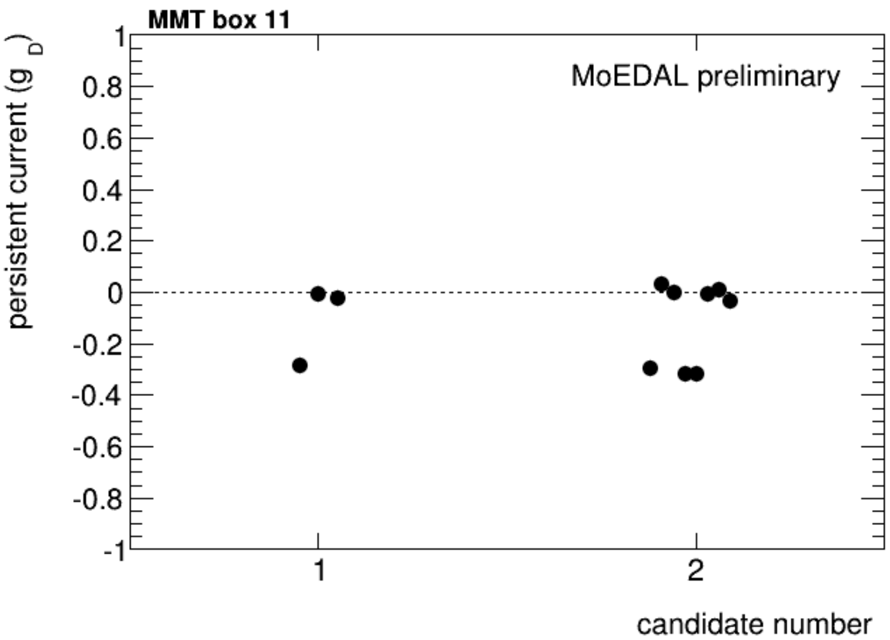
Box 11 measurements

Rods cut into 66 samples of length ranging from 10 to 30 cm



Results of Box 11 measurements



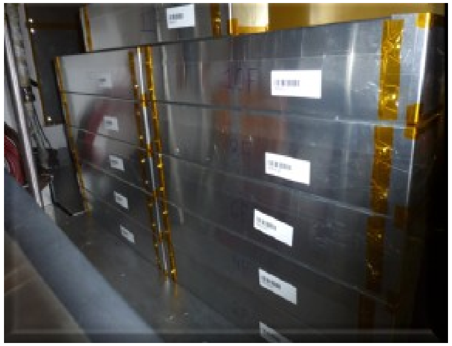


- Left plot shows persistent current after first passage for all samples
- Excellent charge resolution (< 0.1 g_D) except for two outliers at -0.3 g_D
- Both candidates are large (30 cm) samples. Repeated measurements (right) reveal small occasional offset jumps. This is a known effect, observed for large samples (see also EPJC 72, 2212 (2012), arXiv:1206.6793)
- No monopole with charge > 0.5 g_D in MMT box 11

Summary (1)

- Magnetic monopoles are fundamental well-motivated objects
  - Should carry *a multiple* of the Dirac charge
- The LHC collided protons at 8 TeV (will increase to 14 TeV)
  - Provides a unique opportunity to constrain monopole production in an hitherto *unexplored* mass range
- The MoEDAL experiment uses complementary approaches:
  - In-flight detection – track-etch technique
  - Trapping – induction technique

MoEDAL NTDs

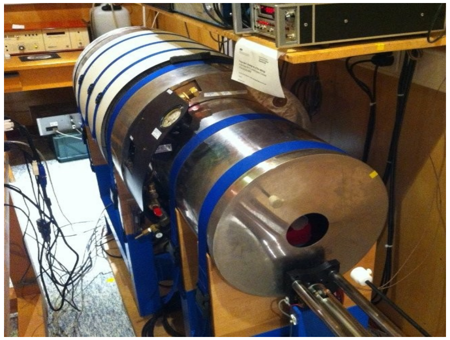


MoEDAL MMT

Summary (2)

- The MoEDAL Magnetic Monopole Trapper (MMT) test array was exposed to 0.75 fb^{-1} of 8 TeV *pp* collisions in 2012
  - First measurements were presented today (9% of the array)
  - Scanning of full MMT array will continue this Summer
  - Probes monopole charges and masses in a range inaccessible to general-purpose experiments, and can provide faster results

Large Hadron Collider



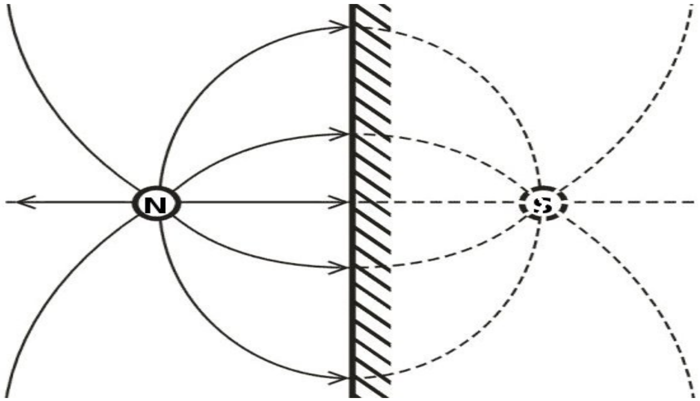
SQUID magnetometer

Extra slides

Monopole binding in matter

- **To atoms**
  - Binding energies of the order of a few eV
- **To nuclei with non-zero magnetic moments**
  - Binding energies of the order of 200 keV

    (Rep. Prog. Phys. 69, 1637 (2006), arXiv:hep-ex/0602040)
- **At the surface of a ferromagnetic**
  - Image force of the order of 10 eV/Å
  - Robust prediction (classical)



Monopole ionisation energy loss

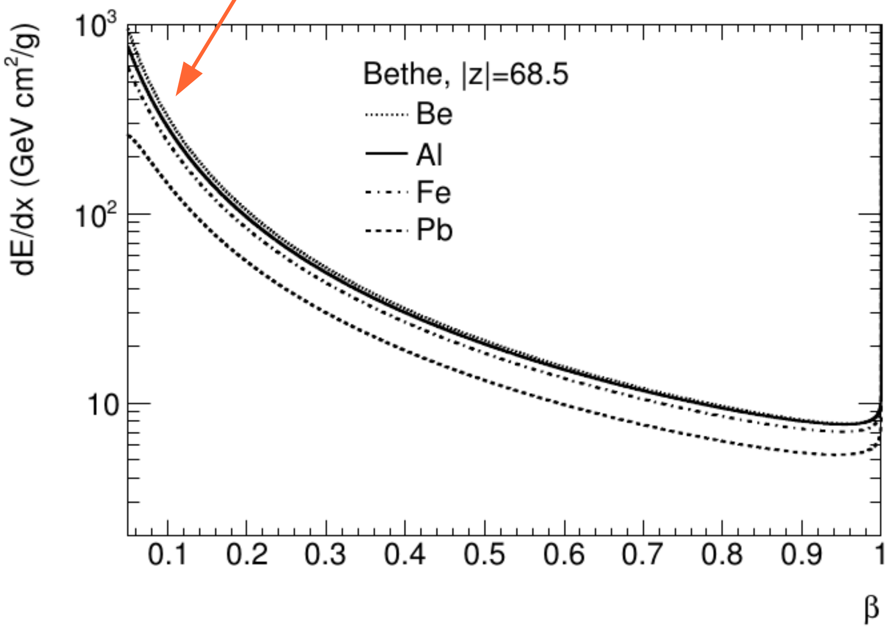
Electric

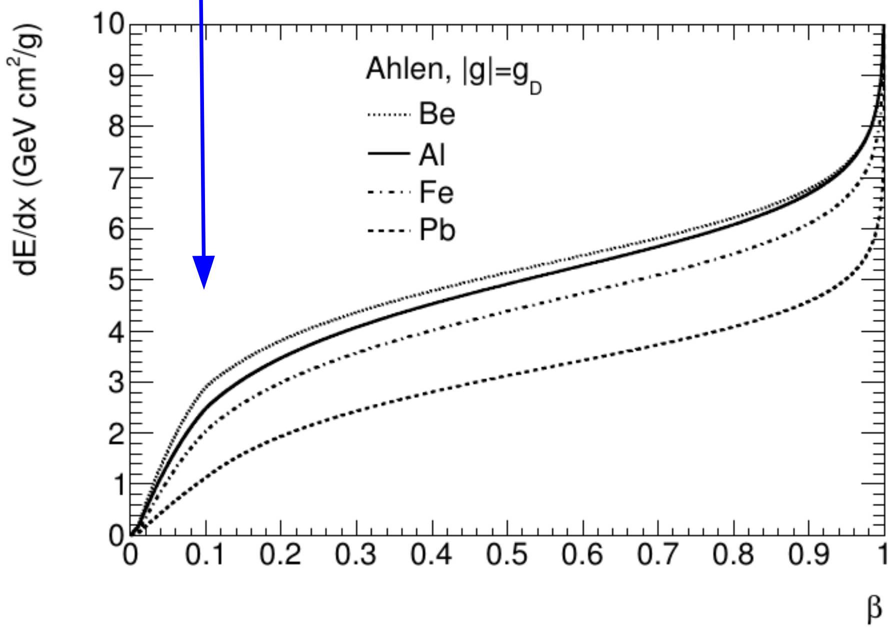
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2\right]$$

Magnetic

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}g^2\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I_m} + \frac{K(|g|)}{2} - \frac{1}{2} - B(|g|)\right]$$

No Bragg peak!





<u>Dirac monopole</u>: $|g_D| = 68.5$ → several thousand times greater d*E*/d*x* than a minimum-ionising $|z|=1$ particle

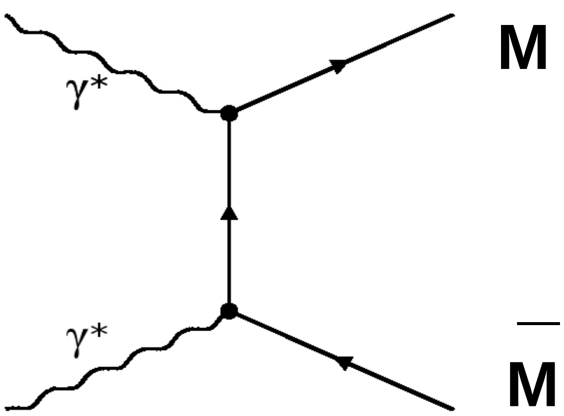
Monopole production

EM coupling constant for Dirac charge = 34.25

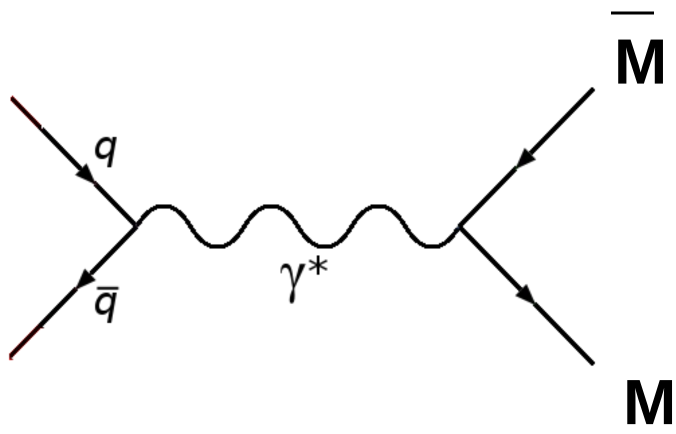
→ non-perturbative dynamics, no reliable cross sections and kinematics!

<u>“Natural” benchmark models:</u>

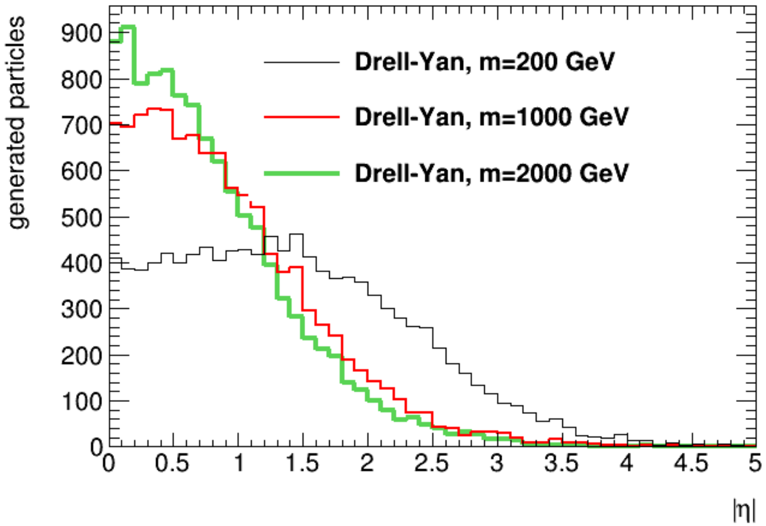
photon fusion

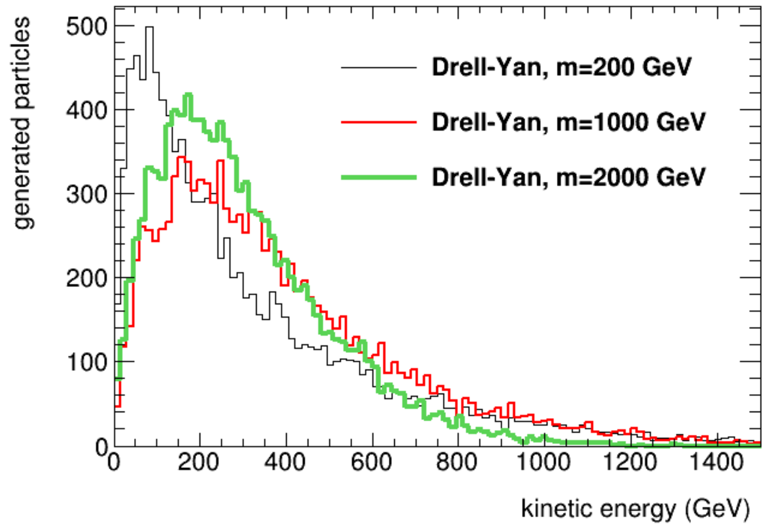


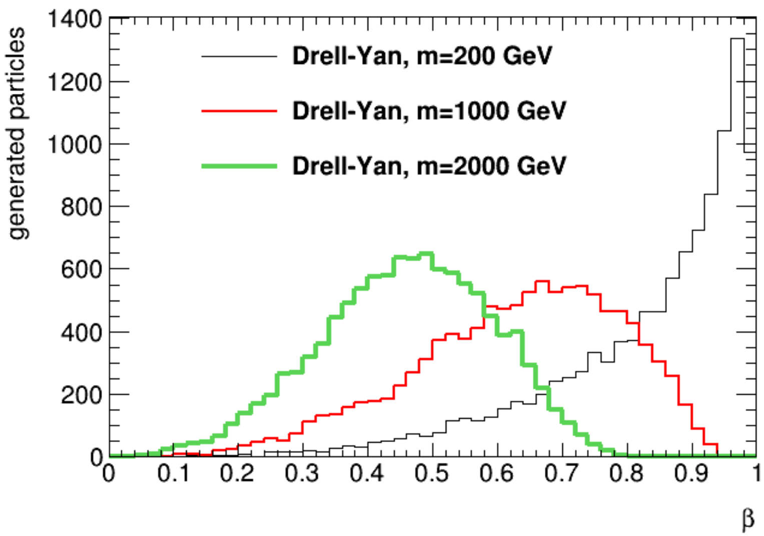
Drell-Yan

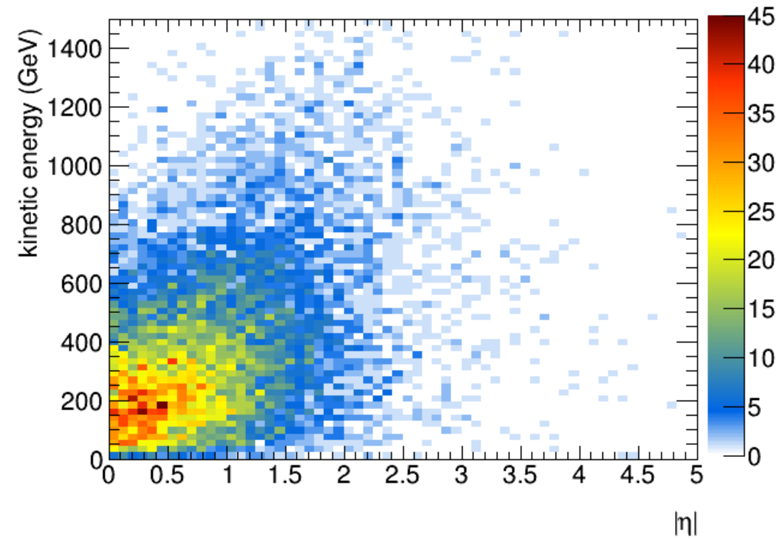


8 TeV monopole production kinematics

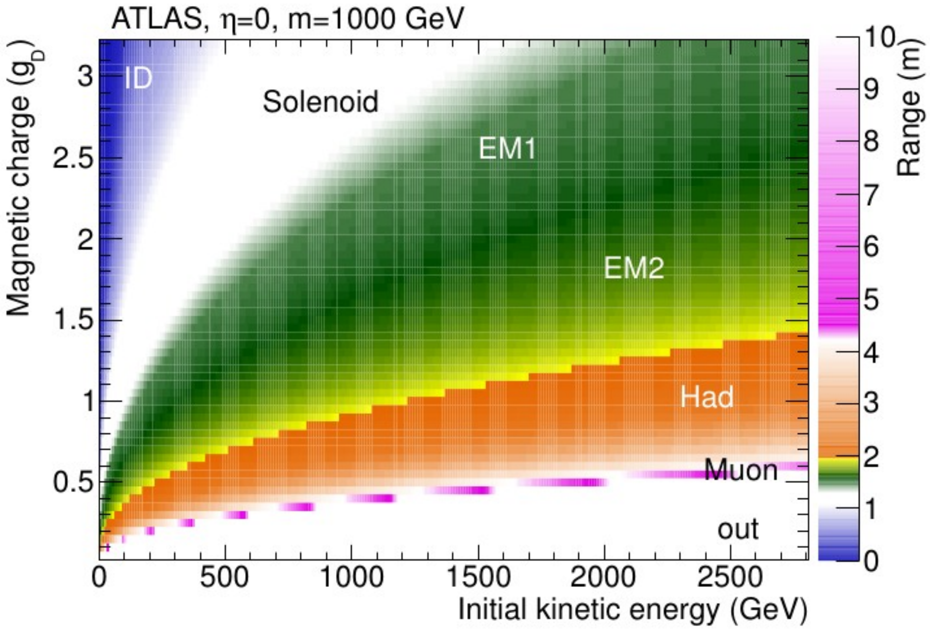


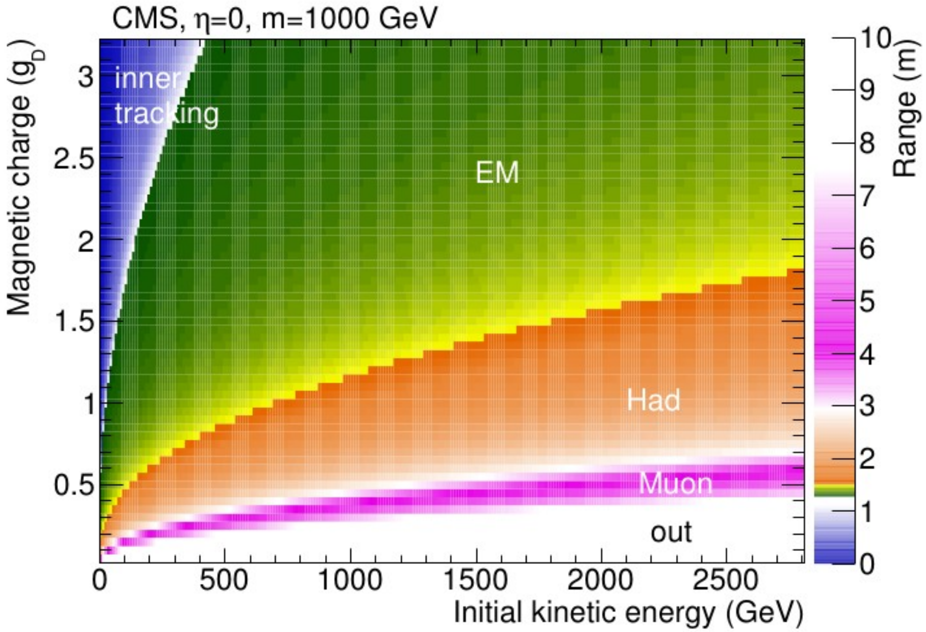






Range of monopoles in ATLAS and CMS

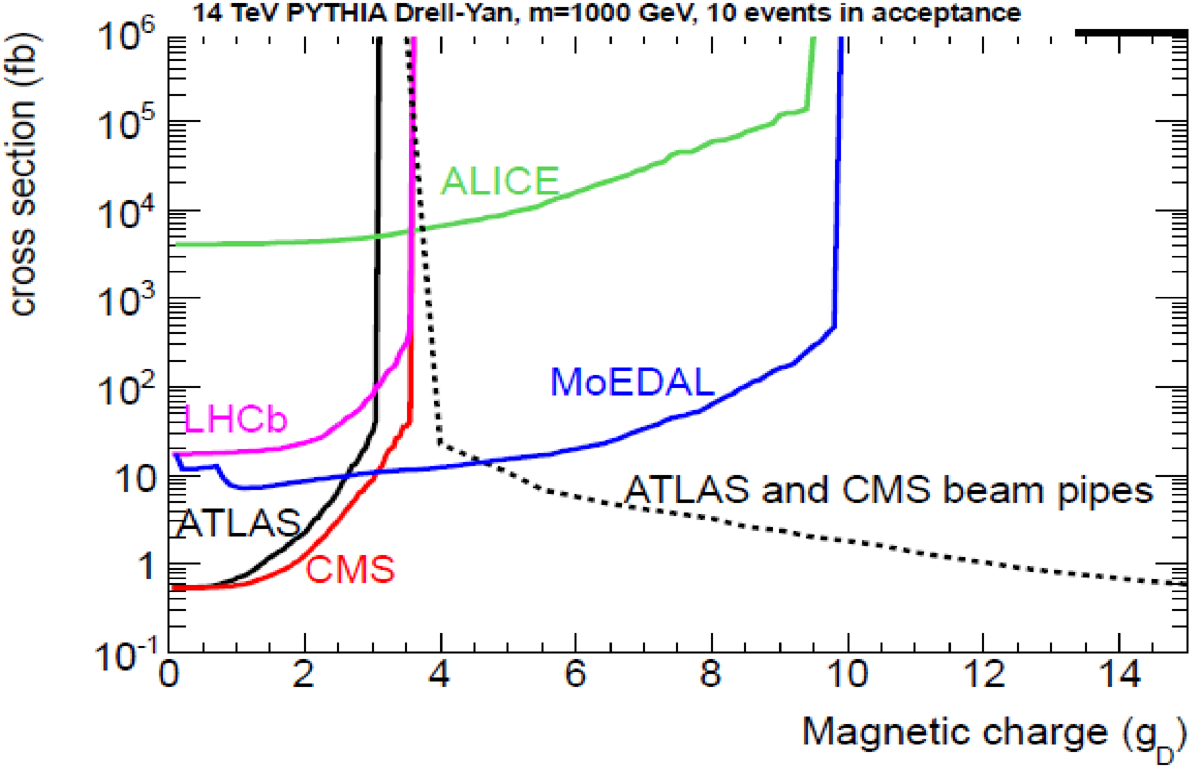




EPJC 72, 1985 (2012), arXiv:1112.2999

Monopoles in 14 TeV collisions: comparison of different LHC experiments

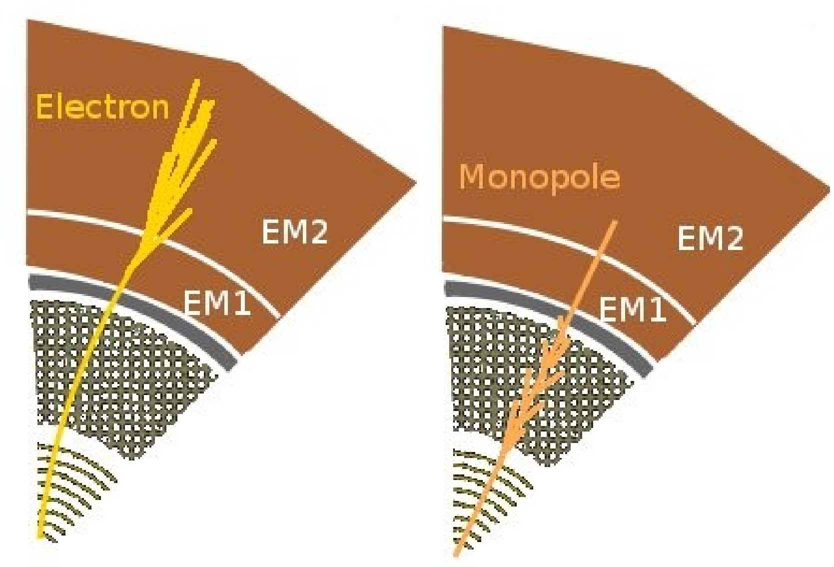
Cross section needed for 10 events within detector acceptance

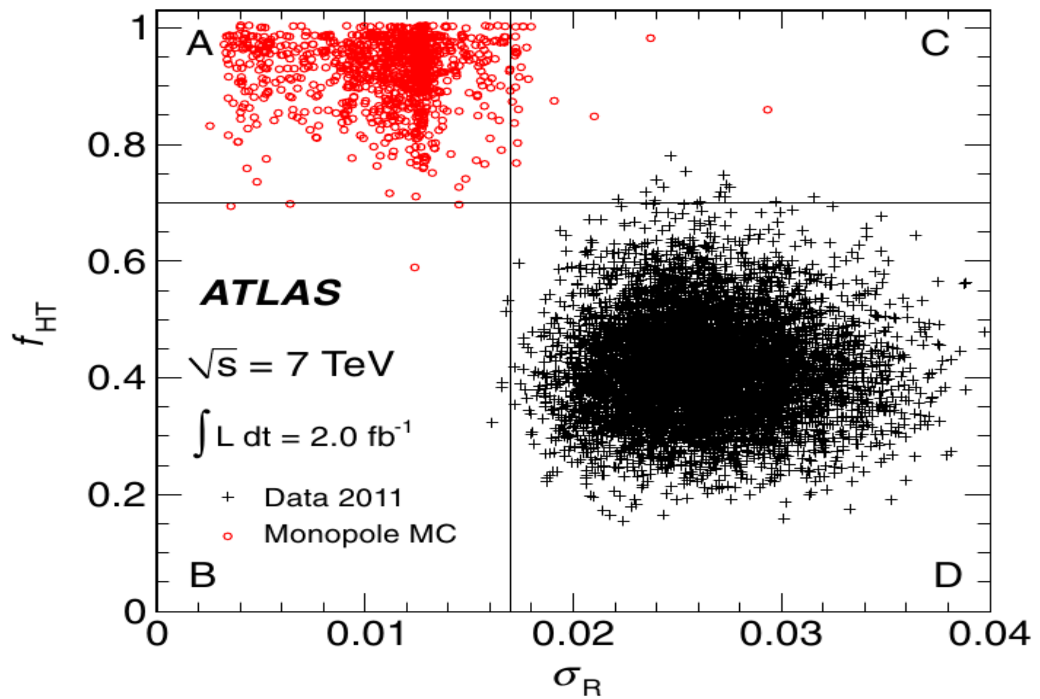


EPJC 72, 1985 (2012), arXiv:1112.2999

ATLAS monopole search

PRL 109, 261803 (2012), arXiv:1207.6411



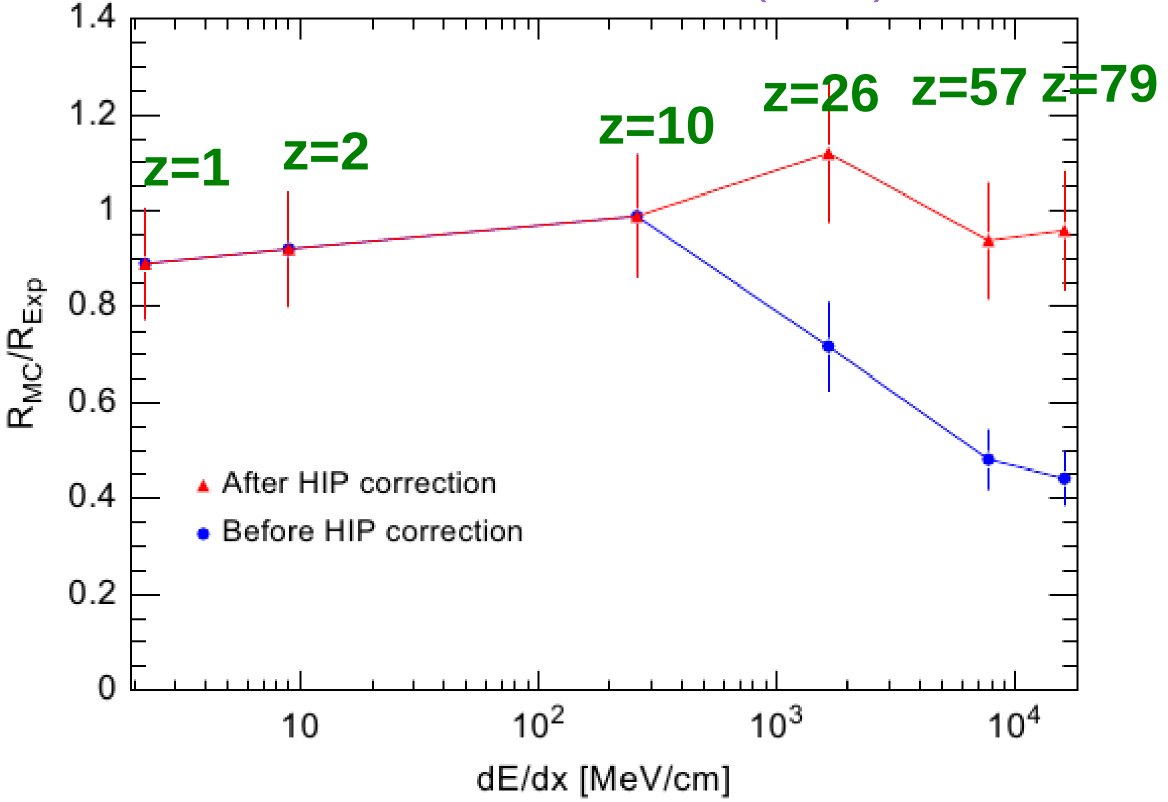


- Electron trigger requires energy in second calorimeter layer (EM2)
  → sensitive to high energy or low charge ($N = 1$)
- Dedicated tracking and simulation
- Signature: high ionisation hits and narrow energy deposition
- Results: cross section limits 2-30 fb for masses up to 1500 GeV

Visible energy in Liquid-Argon

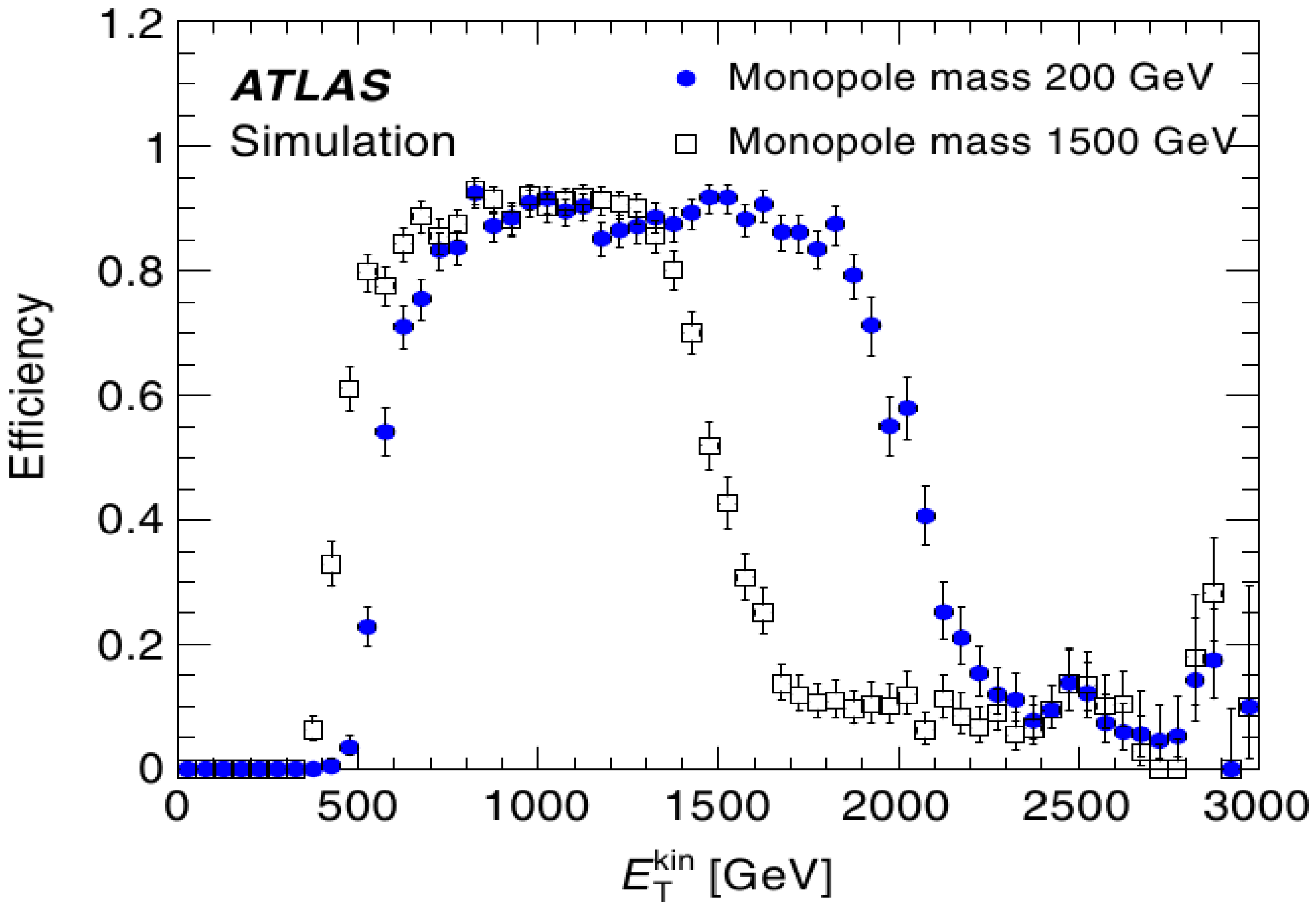
- Birks' law models electron-ion recombination effects
  - over-suppresses signal at high dE/dx
- For high charges, need HIP correction obtained from heavy ion data

Nucl. Inst. Meth. A 664, 111 (2012)



ATLAS monopole search – efficiency

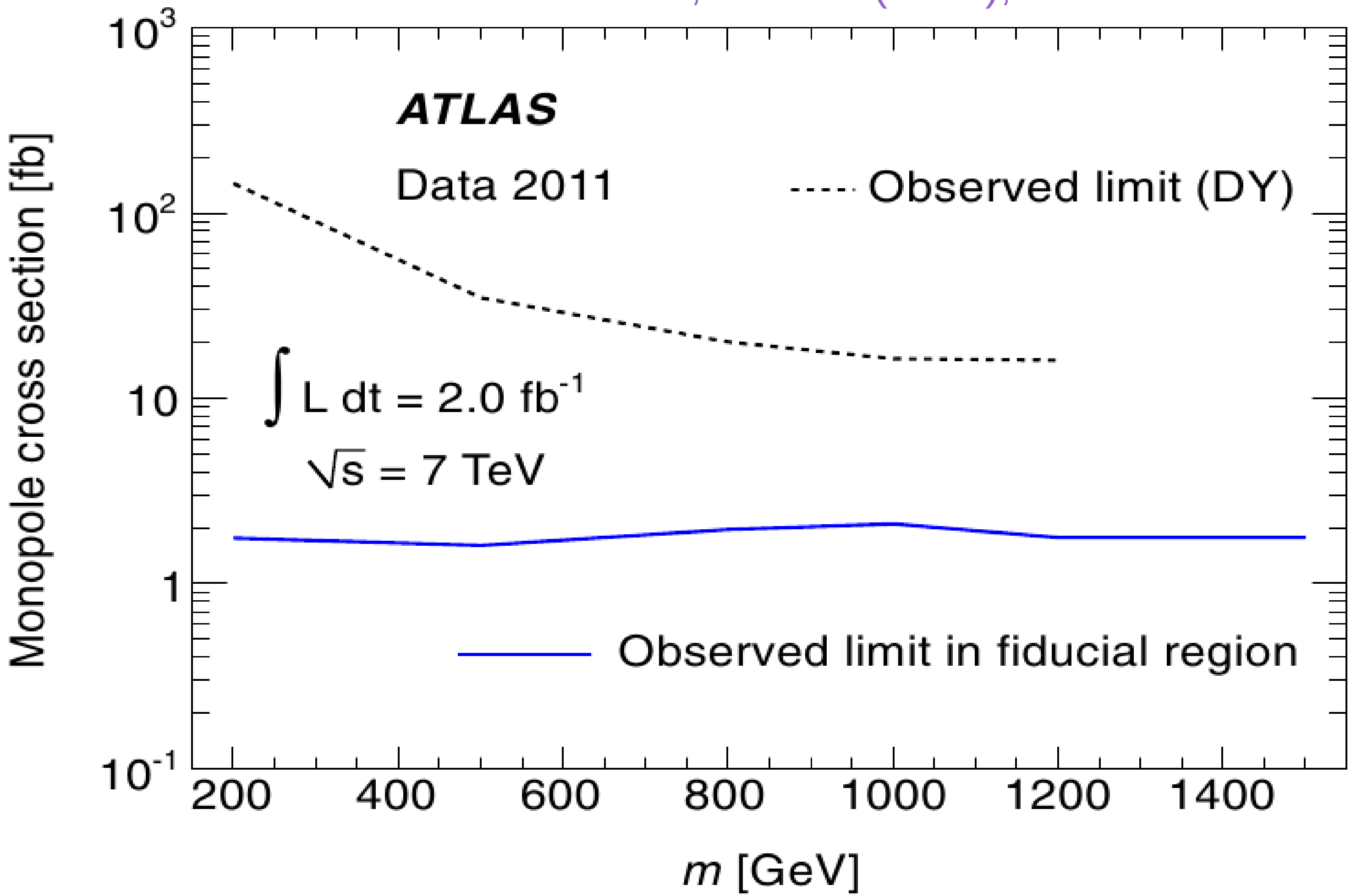
PRL 109, 261803 (2012), arXiv:1207.6411



ATLAS monopole search – results

- Valid for Dirac (*N*=1) monopoles
- Blue curve is model-independent (factoring out acceptance)

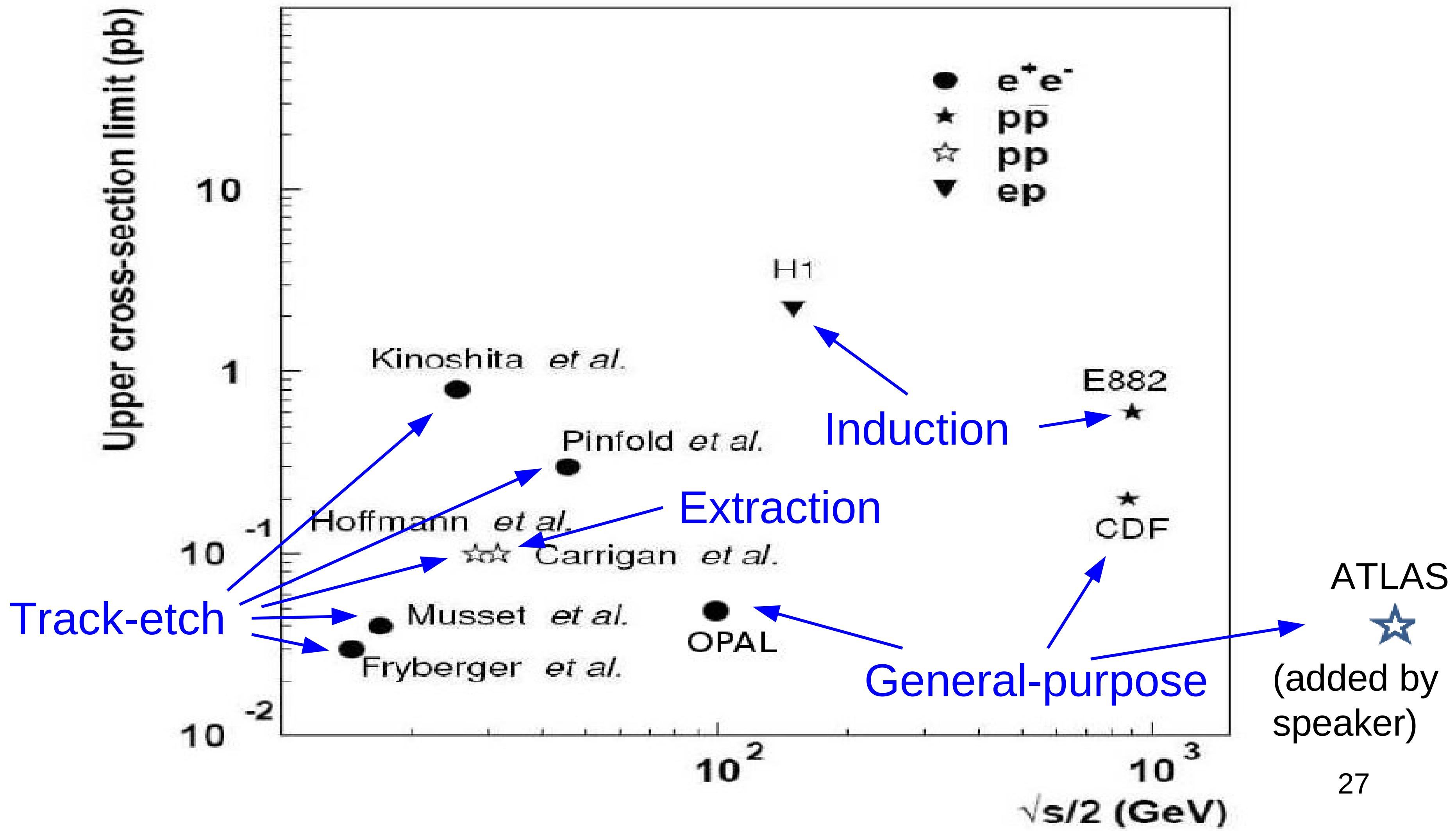
PRL 109, 261803 (2012), arXiv:1207.6411



Collider cross section limits for a Dirac monopole

Each limit is valid in a given mass range,
generally assuming Drell-Yan like pair production mechanism

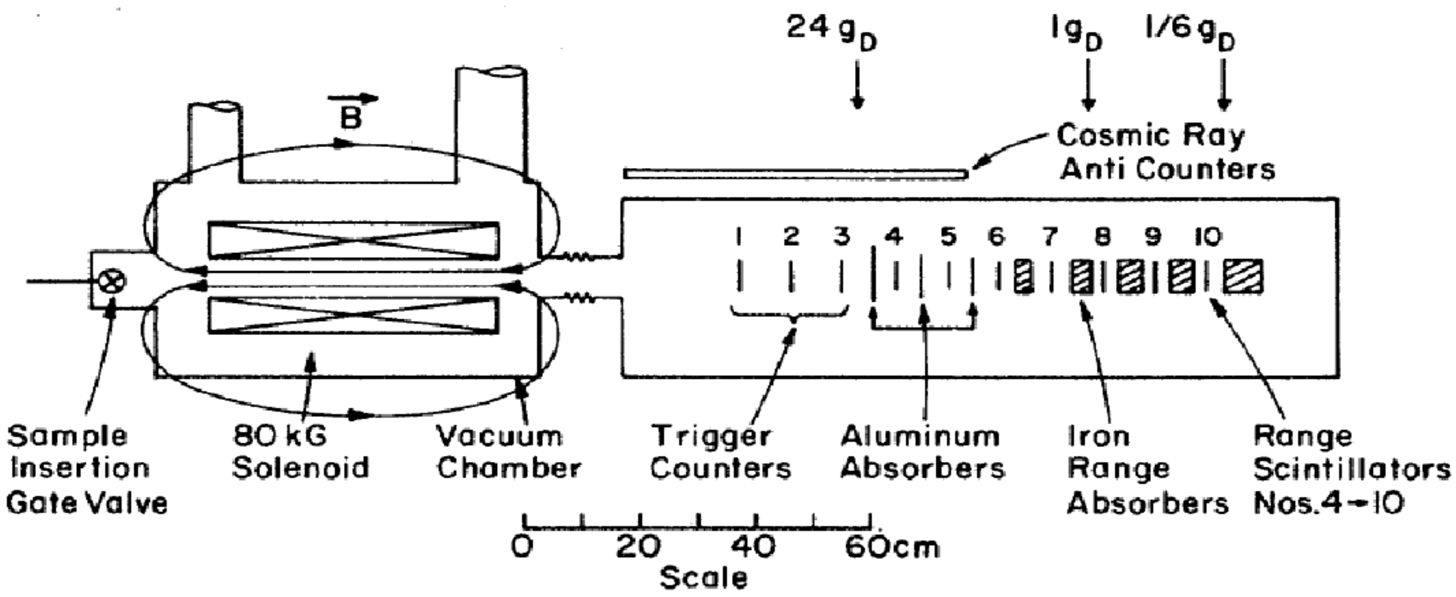
Phys. Rept. 438, 1 (2007), arXiv:hep-ph/0611040



Trapping array experiment at Fermilab

- Steel beam dump exposed to 300 GeV protons
  - Scanned with a monopole extraction device
  - Assumptions different than for the induction technique (arguably less reliable)

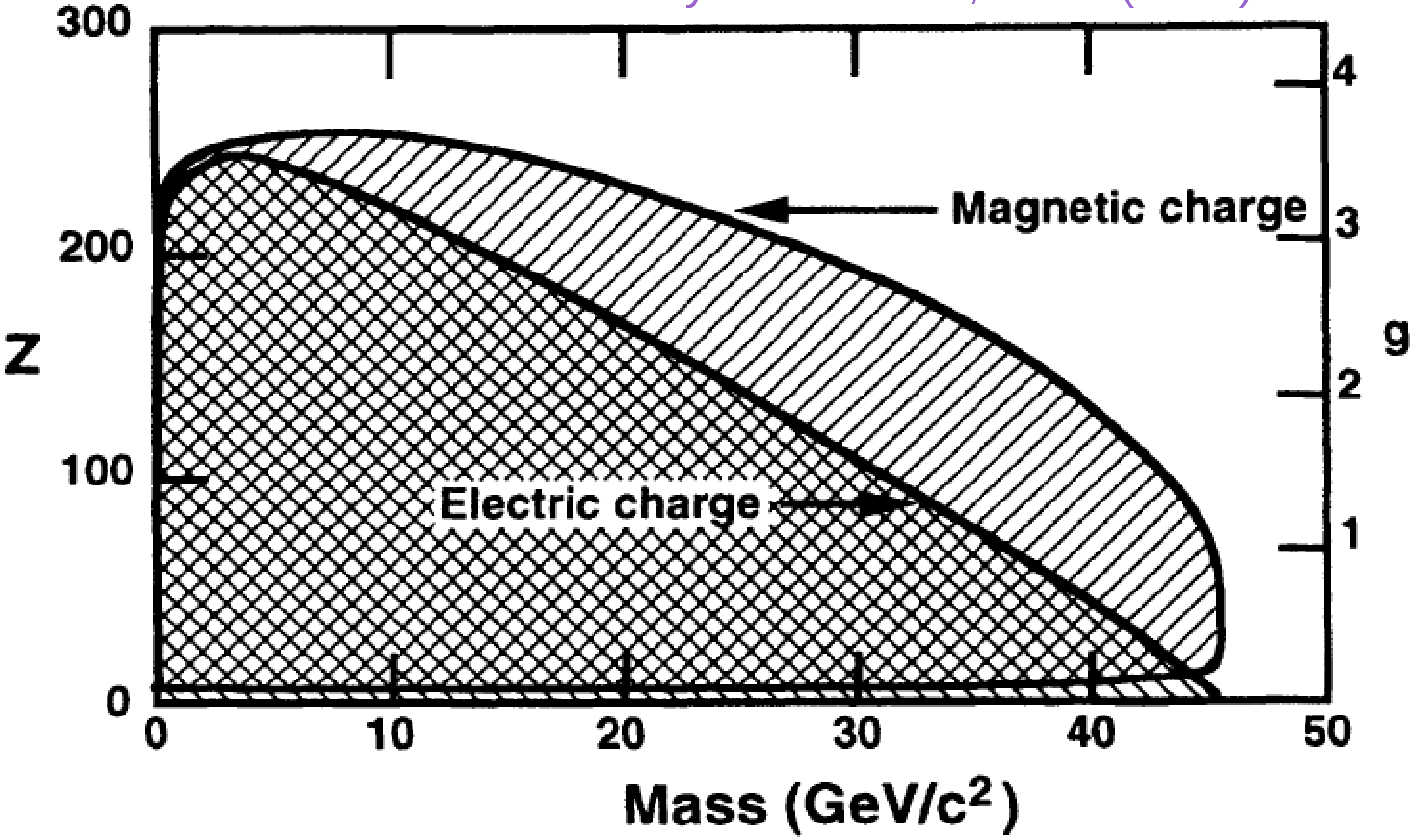
Phys. Rev. D 8, 3717 (1973)



MODAL experiment at LEP1

- Nuclear-track detectors surrounding I5 interaction point
- 91 GeV electron-positron collisions
- 0.3 pb limit in dashed regions

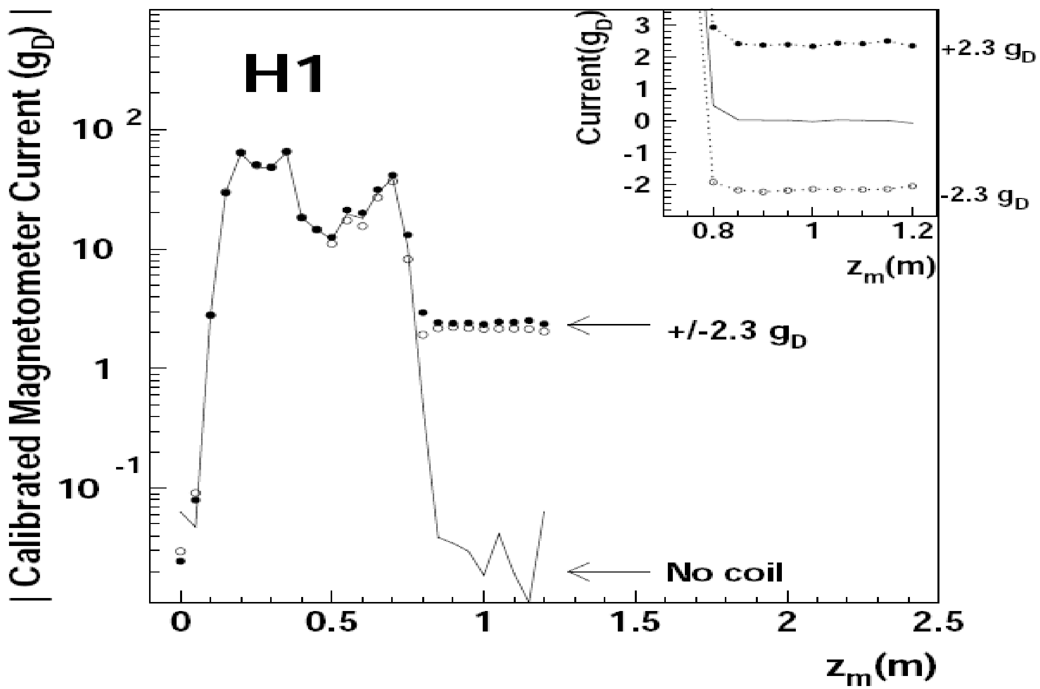
Phys. Rev. D 46, R881 (1992)



Monopole trapping in H1 beam pipe

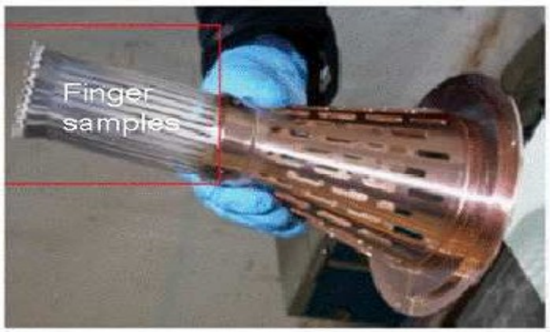
- HERA collider, 300 GeV electron-proton collisions
- Monopoles and dyons with very high magnetic charges would stop in the aluminium beam pipe
  - Scanned with SQUID magnetometer (induction technique)
- 0.1 – 1 pb limit (up to 140 GeV monopole with $g \geq g_D$)

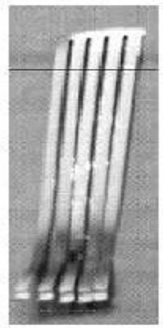
EPJC 41, 133 (2005), arXiv:hep-ex/0501039

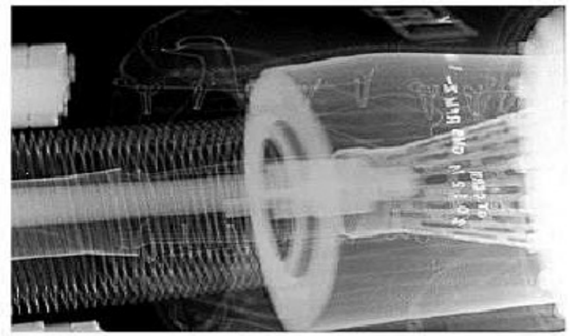


Recent magnetometer tests for trapped monopoles searches

Proof-of-principle using accelerator material near CMS

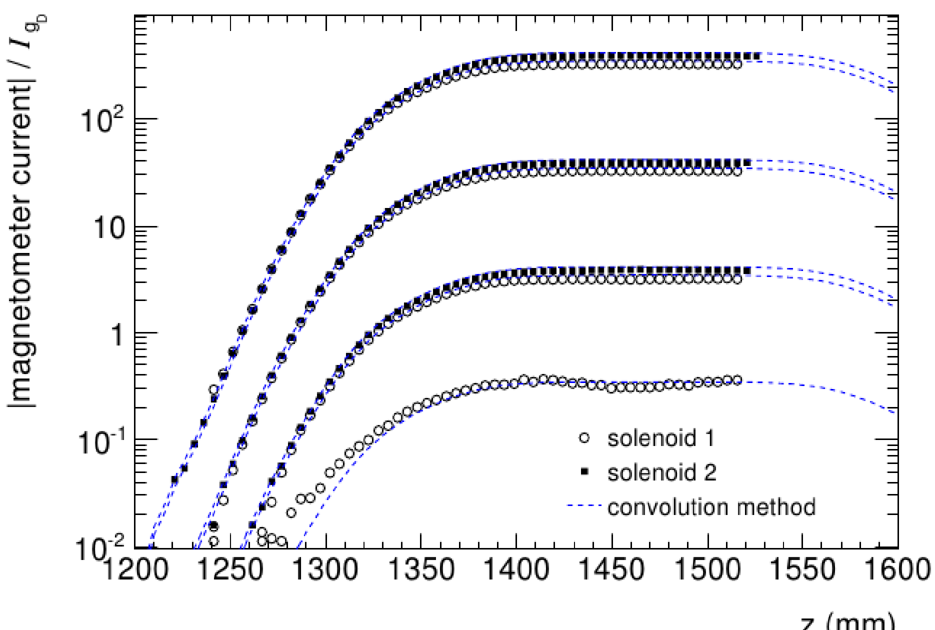




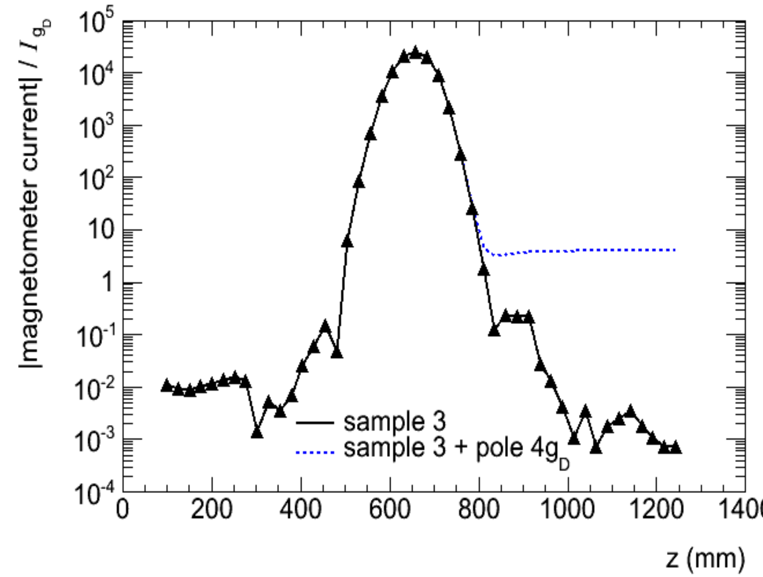


X-ray image of defective plug-in module

Calibration cross-check with long, thin solenoids



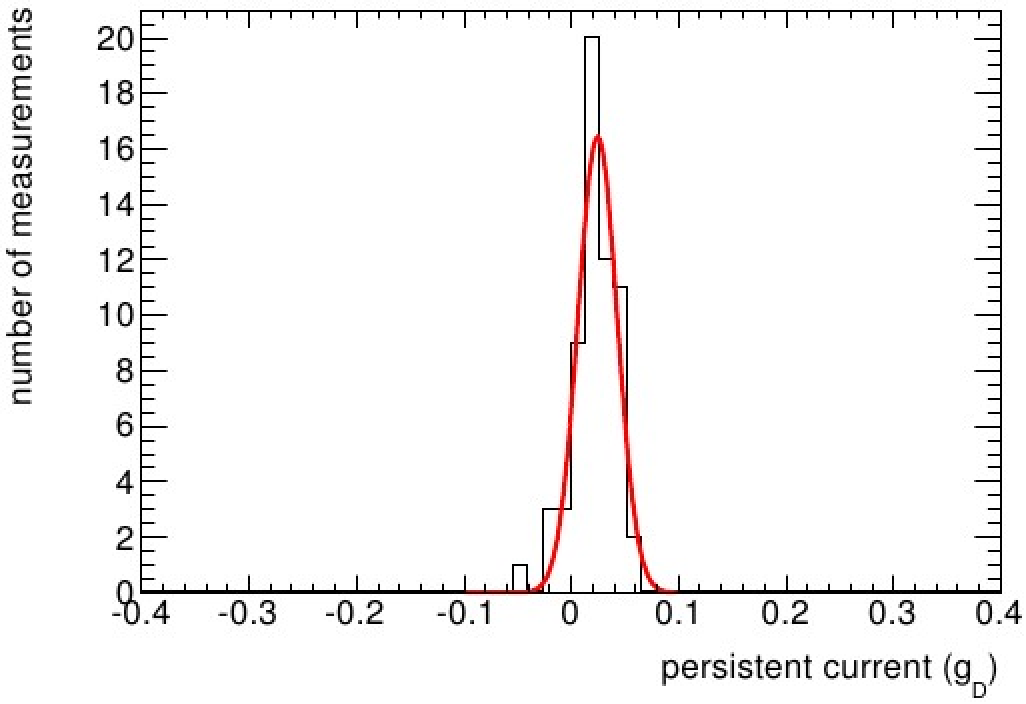
EPJC 72, 2212 (2012), arXiv:1206.6793



MMT design

- Material: Aluminium
  - Large nuclear dipole moment (spin 5/2) → likely to bind monopoles
  - No activation
  - Low magnetisation
  - Cheap
- Boxes:
  - 18 rods 60 cm long and 2.5 cm diameter
  - Nicely fits magnetometer sample holder
- 2012 array: 11 boxes in front of VELO vacuum chamber
- 2015 arrays: In front, on the side, and below the VELO chamber

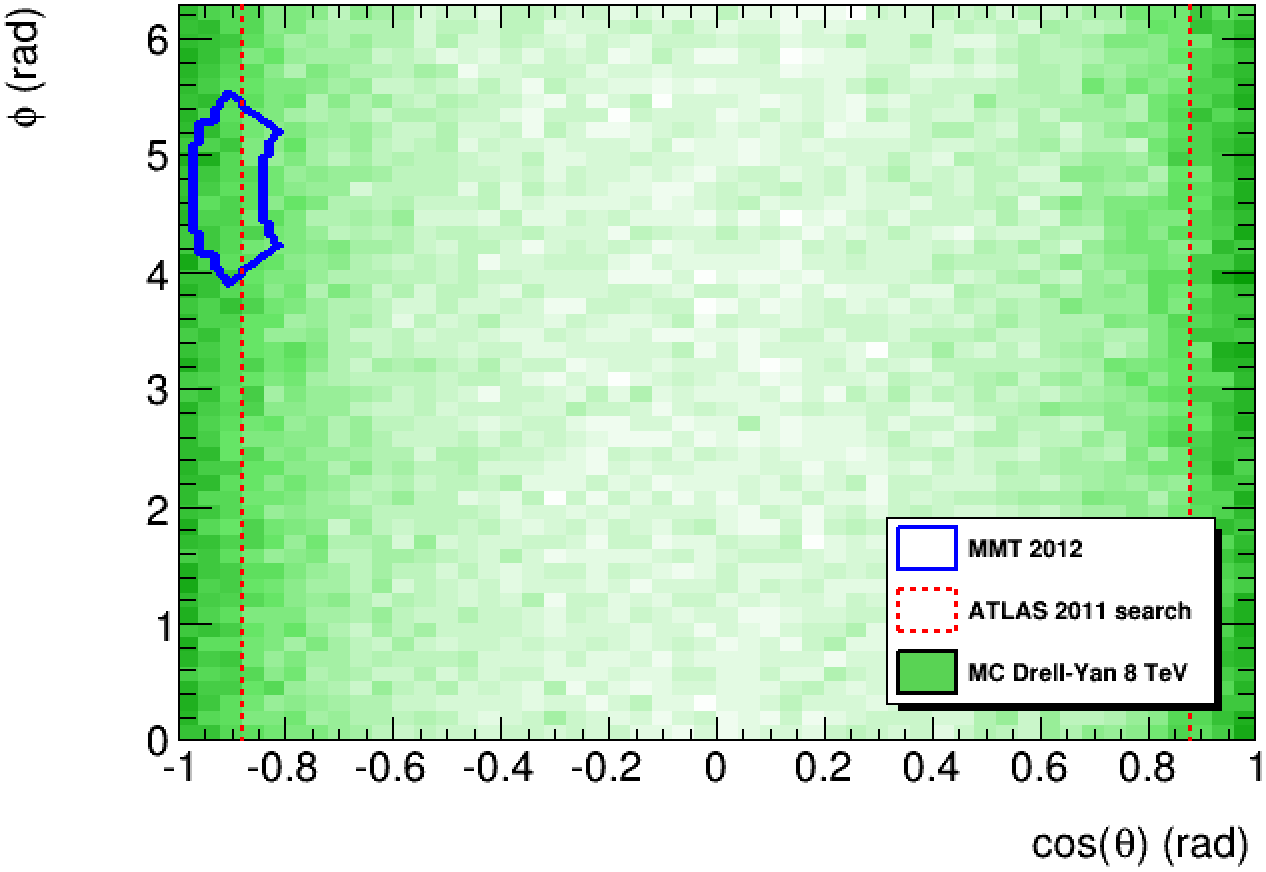
MMT tests with magnetometer



- Aluminium modules identical to those used in the MMT setup
- Monopoles with charge down to $0.5g_D$ can be identified without ambiguity

MMT 2012 – solid angle

Array covers 1.3 % of the total solid angle



MMT 2012 – integrated luminosity

Array exposed to 0.75 fb^{-1} of 8 TeV *pp* collisions