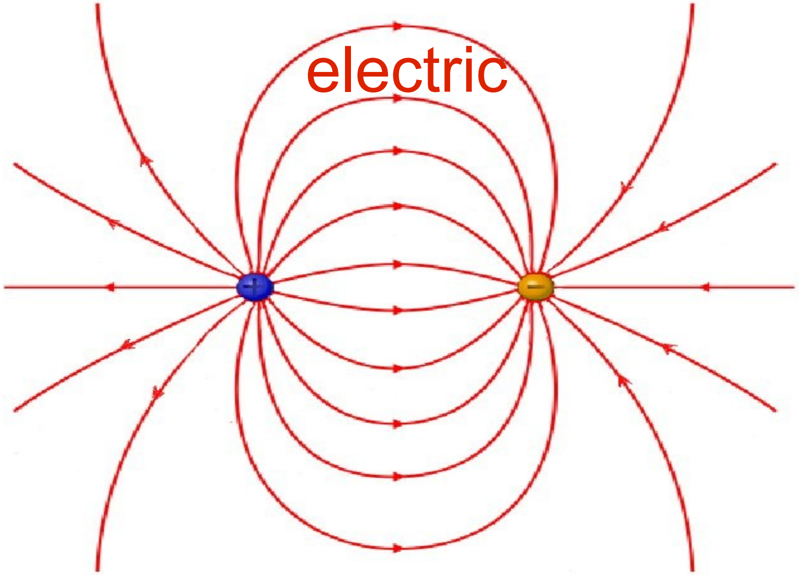
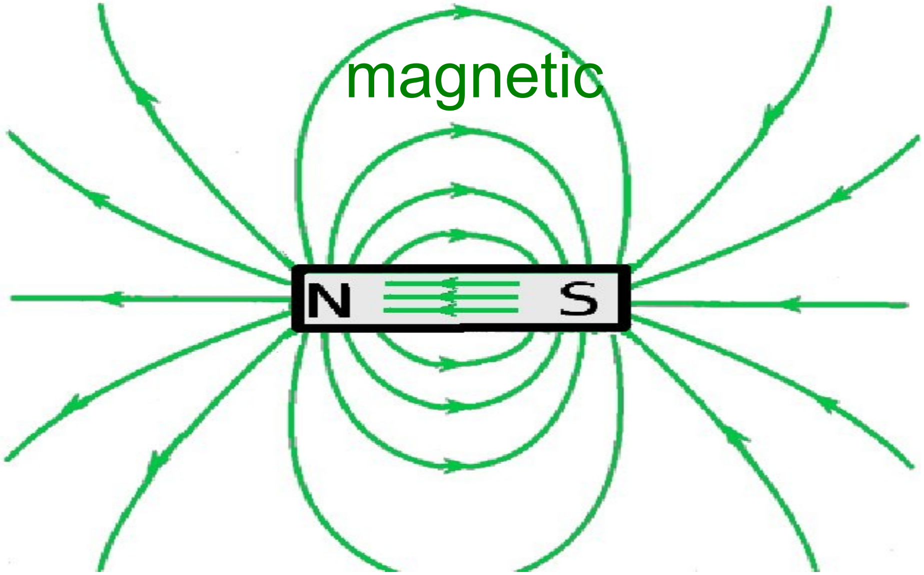
Hunting for magnetic monopoles in bulk matter

Philippe Mermod (University of Geneva)
Seminar, ETH Zurich
18 April 2013

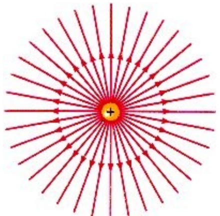
Magnetic monopole – the basics

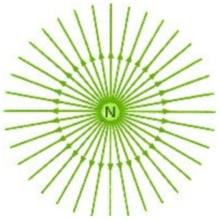
- Divergent magnetic field lines are not seen in nature
  - If you break a dipole magnet, you get two dipole magnets!



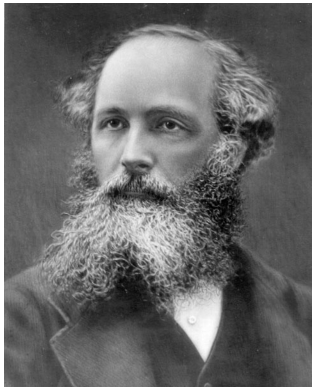


- Poles of electric field exist because electrically charged particles (e.g. electrons) exist
  - Are there magnetic equivalents?



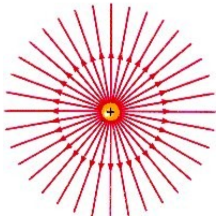


Maxwell's equations (1862)



Without monopoles

$$\nabla \cdot \mathbf{E} = 4\pi \rho_e$$



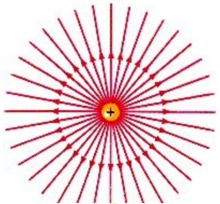
$$\nabla \cdot \mathbf{B} = 0$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

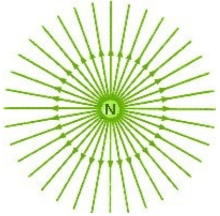
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

With monopoles

$$\nabla \cdot \mathbf{E} = 4\pi \rho_e$$



$$\nabla \cdot \mathbf{B} = 4\pi \rho_m$$

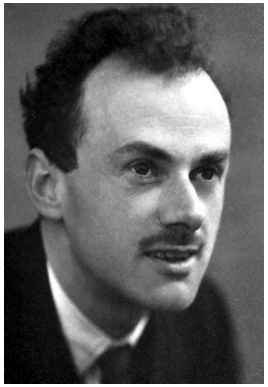


$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j_m}$$

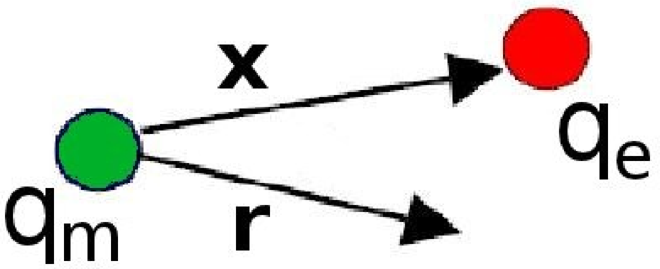
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

Dirac's argument

Proc. Roy. Soc. A 133, 60 (1931)



Field angular momentum of electron-monopole system is quantised:



$$\mathbf{L} = \int \mathbf{r} \times \mathbf{E} \times \mathbf{B}\, d\mathbf{r} = \frac{\mu_0 q_e q_m}{4\pi} \hat{\mathbf{x}}$$

$$\Rightarrow q_e q_m = n \frac{h}{\mu_0} \; (n \text{ integer number})$$

Explains quantisation of electric charge!

- Fundamental magnetic charge (*n* = 1):

$$g_D = \frac{1}{2\alpha} = 68.5 \; (\text{with } q_m = gec \text{ and } q_e = e)$$

- Monopoles should be very highly ionising!

Schwinger's argument

Phys. Rev. 144, 1087 (1966)

Postulate particle carrying both electric and magnetic charges → ***dyon***

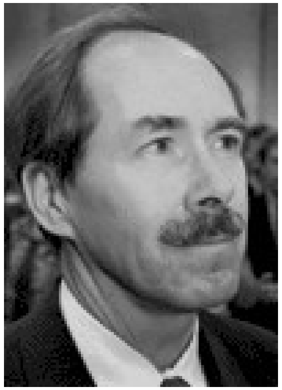
- Quantisation of angular momentum with two dyons (q_{e1},q_{m1}) and (q_{e2},q_{m2}) yields:

$$q_{e1}q_{m2} - q_{e2}q_{m1} = 2n\frac{h}{\mu_0} \ (n \text{ integer number})$$

- Fundamental magnetic charge is now $2g_D$!
- With $|q_e|$=1/3*e* (down quark) as the fundamental electric charge, it even becomes $6g_D$

't Hooft and Polyakov's argument

Nucl. Phys. B79, 276 (1974)

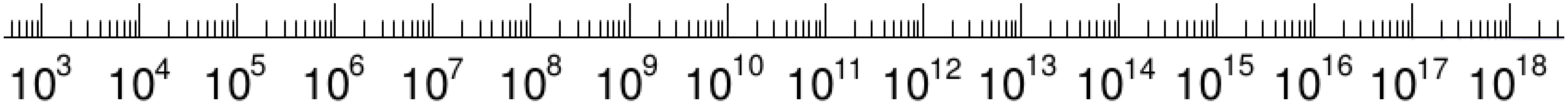


Assume the U(1) group of electromagnetism is a subgroup of a broken gauge symmetry

- Then monopoles arise as solutions of the field equations. Very general result!
- Monopole mass typically of the order of the unification scale

LHC reach

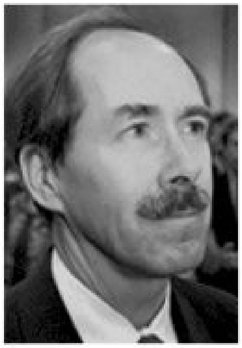
GUT monopole



Possible monopole mass rage (GeV)

Dirac's quantisation condition

Schwinger's dyons



t'Hooft's GUT monopoles

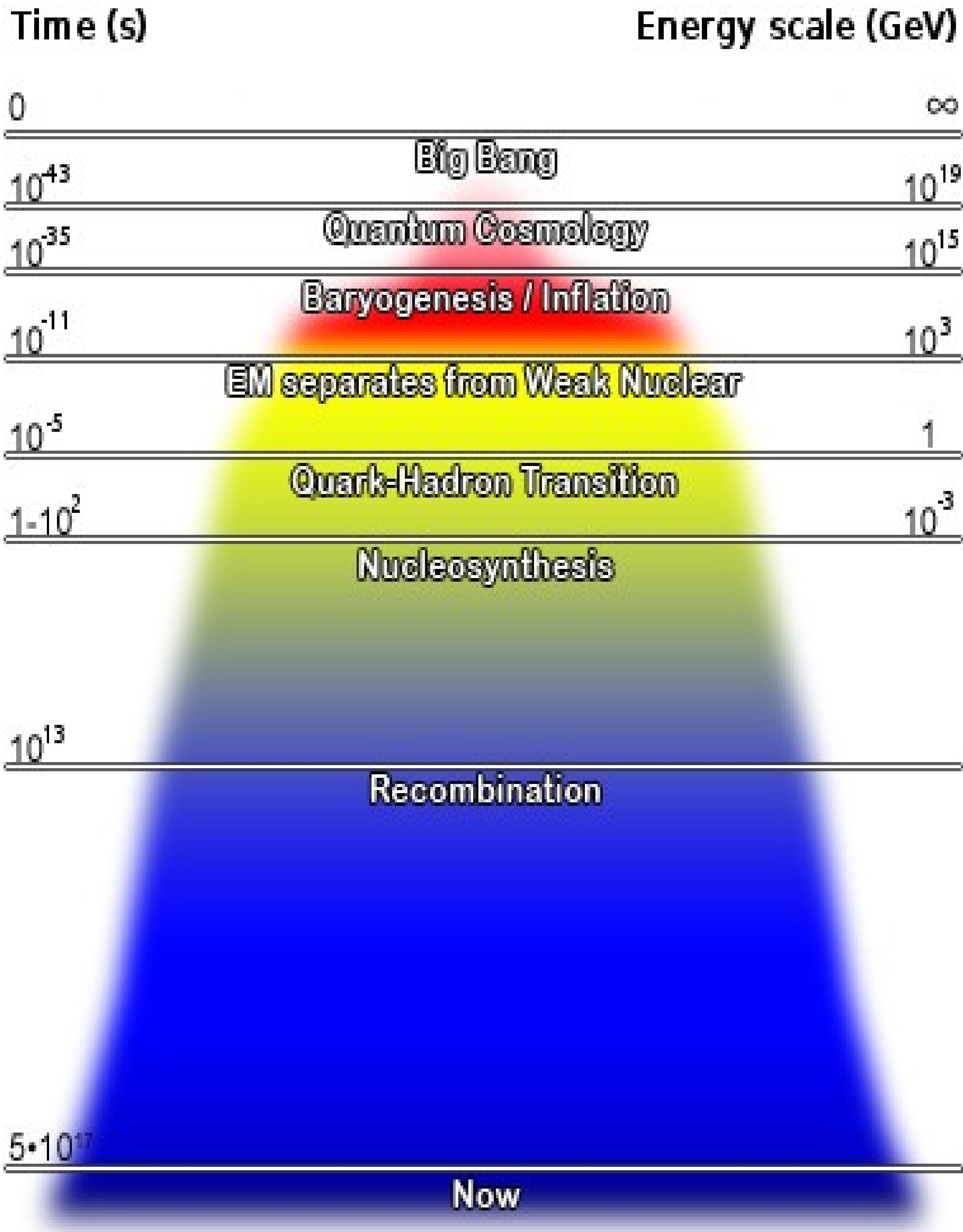
Bevatron **AGS** **IHEP** **ISR** **Fermilab** **PETRA** **SLAC** **TRISTAN** **LEP** **Tevatron** **HERA** **LHC**

So, what we learned so far...

- There is no fundamental reason why monopoles would not exist
  - But several arguments indicate that they should!
  - Monopoles would be stable and produced in pairs, and carry a multiple of the Dirac charge → highly ionising
- Monopoles with masses up to the TeV scale would be produced at high-energy colliders
  - That would almost certainly be noticed in the measurements
  - A convincing way exclude or discover them
- Grand Unification predicts much higher masses
  - The monopole mass may be treated as a free parameter
  - But how can we probe higher masses?

Primordial Monopoles

- Big Catastrophe: standard cosmology predicts enormous monopole density!
- Inflation theory solves this problem by diluting the monopoles
- Huge uncertainty on relic monopole abundances



Monopole classification

Secondary, produced in collisions:

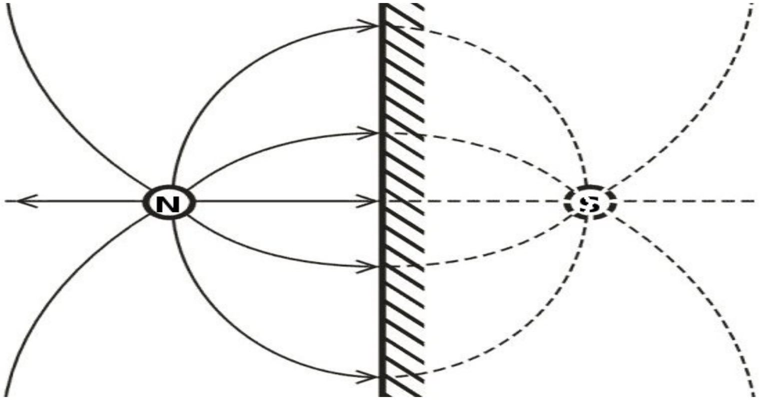
- **Cosmic rays** impacting celestial bodies
  - Probe cross section for given cosmic ray energy spectrum
- **Particle colliders**
  - Probe cross section in limited mass range

Primordial, produced in early universe:

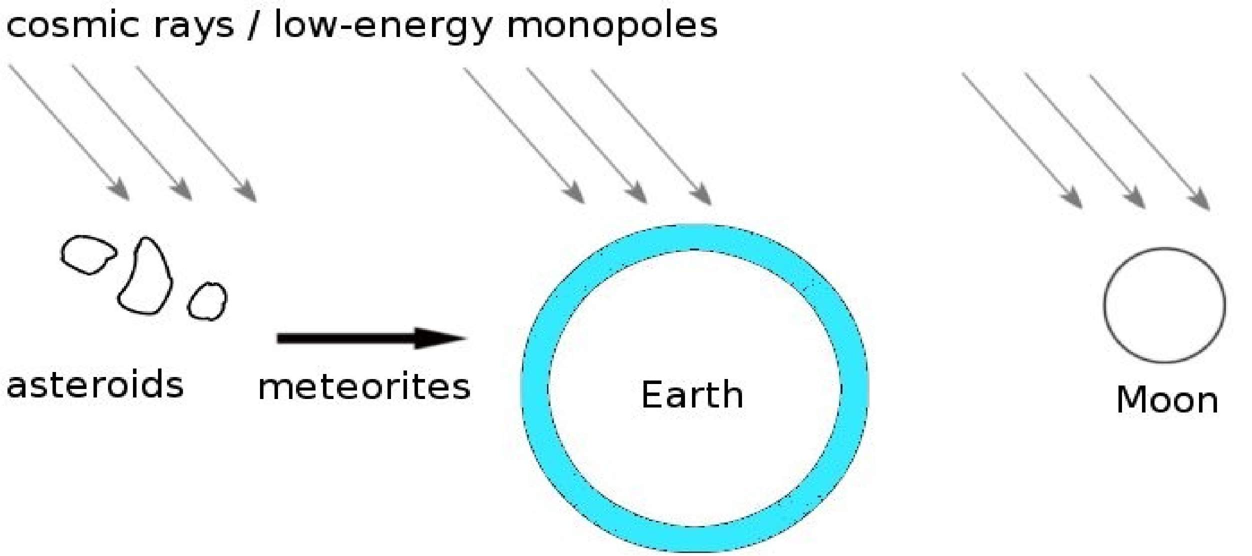
- **Cosmic**, moving freely through outer space
  - Probe flux in given mass range for given energy spectrum
- **Stellar**, bound in matter before star formation
  - Probe density in given medium

Monopole binding in matter

- **To atoms and molecules**
  - Binding energies of the order of a few eV
- **To nuclei with non-zero magnetic moments**
  - Binding energies of the order of 200 keV
- **At the surface of a ferromagnetic**
  - Image force of the order of 10 eV/Å
  - **Robust prediction** (classical)



Early searches for monopole in matter



Before 1980s, searches mostly focused on model of secondary cosmic ray production or thermalised cosmic monopoles

- In asteroids → meteorites
- In Earth's atmosphere → air, seawater, sediments
- In Moon's surface → moon rocks

- Up to billions years exposure time
- Low mass generally assumed
  - For masses >> GeV the game changes completely

Early searches with extraction techniques

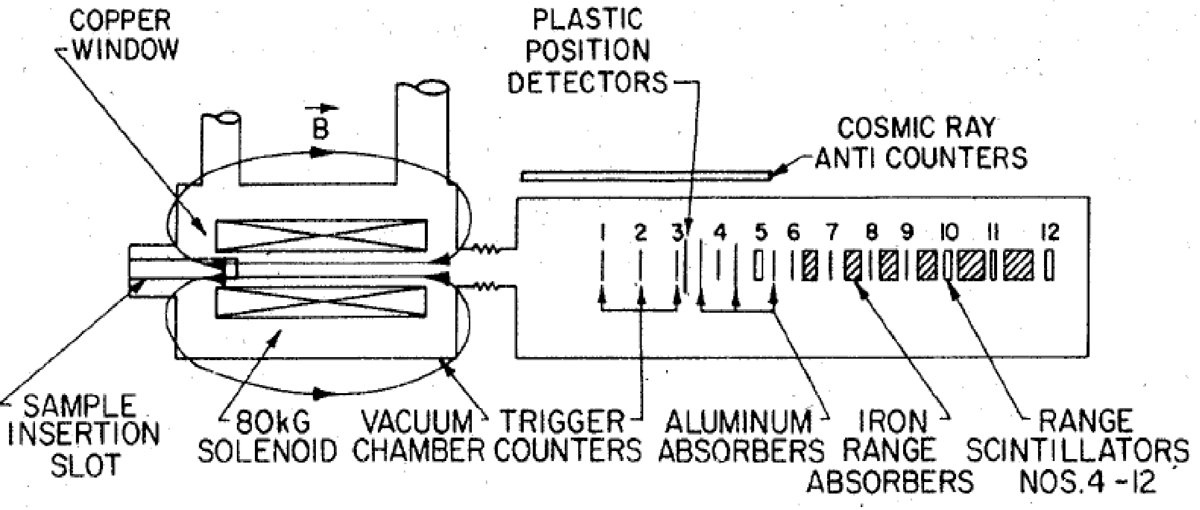
(1960s – 1970s)

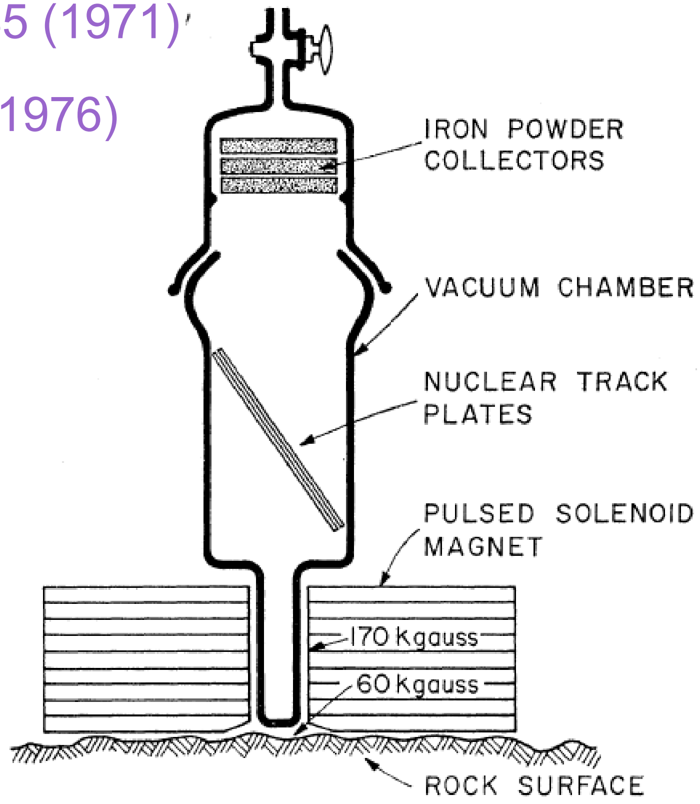
Principle: strong magnetic field used to extract monopole from sample and accelerate it through detector device

- Extraction achieved by heating or pulsed magnetic field
  - Even monopoles which are strongly bound would drag whole atoms with them if they reside on the material surface
- Detectors sensitive to the high ionisation energy loss expected for a monopole
  - Scintillators
  - Nuclear track detectors

Extraction searches, materials probed:

- Meteorite fragment Nucl. Phys. 49, 87 (1963)
- Magnetite and meteorite surface Phys. Rev. 132, 387 (1963)
- Deep-sea manganese nodules Phys. Rev. 177, 2029 (1969)
- Deep-sea sediments Phys. Rev. D 4, 1285 (1971)
- Air and sea water Phys. Rev. D 13, 1823 (1976)





Extraction technique – discussion

- More steps = more uncertainties
    1) Extraction efficiency
    2) Acceleration and collimation efficiency – depends on charge and mass
    3) Detection efficiency – relies on energy loss
- Setup optimised for given mass range
- Can only extract monopoles out of a very thin sample layer → low effective amount of material probed

In the early 1970s, with the invention of superconducting magnetometers, a better method emerged

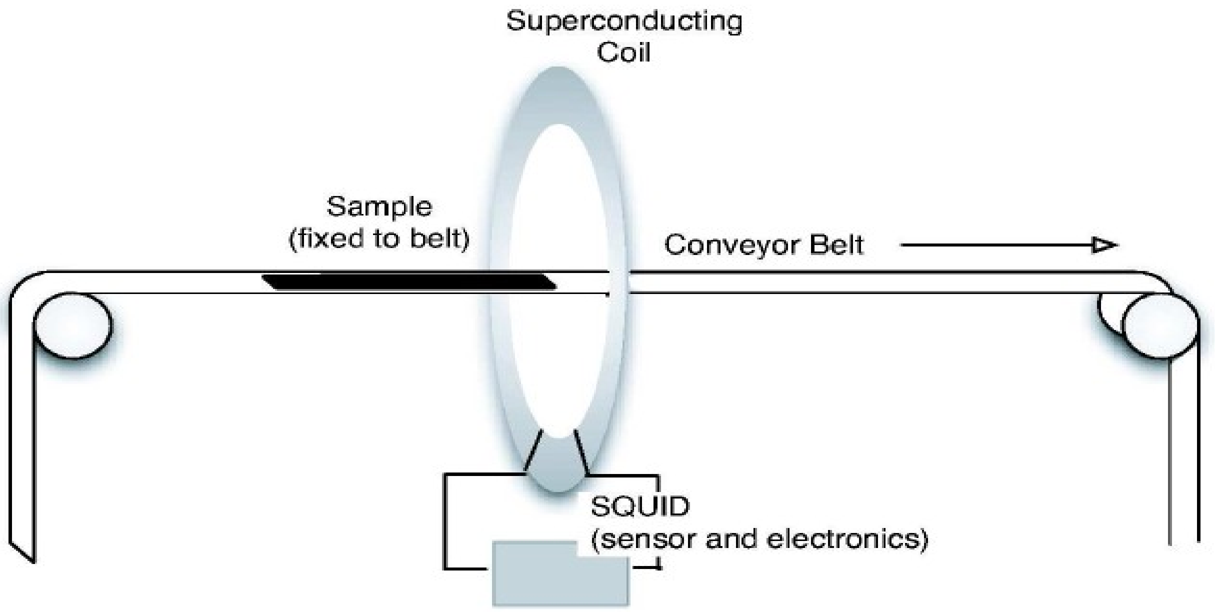
Detection: induction technique

(1970s – today)

Principle: moving magnetic charge induces electric field

Tiny permanent current measured after passage of sample through superconducting coil

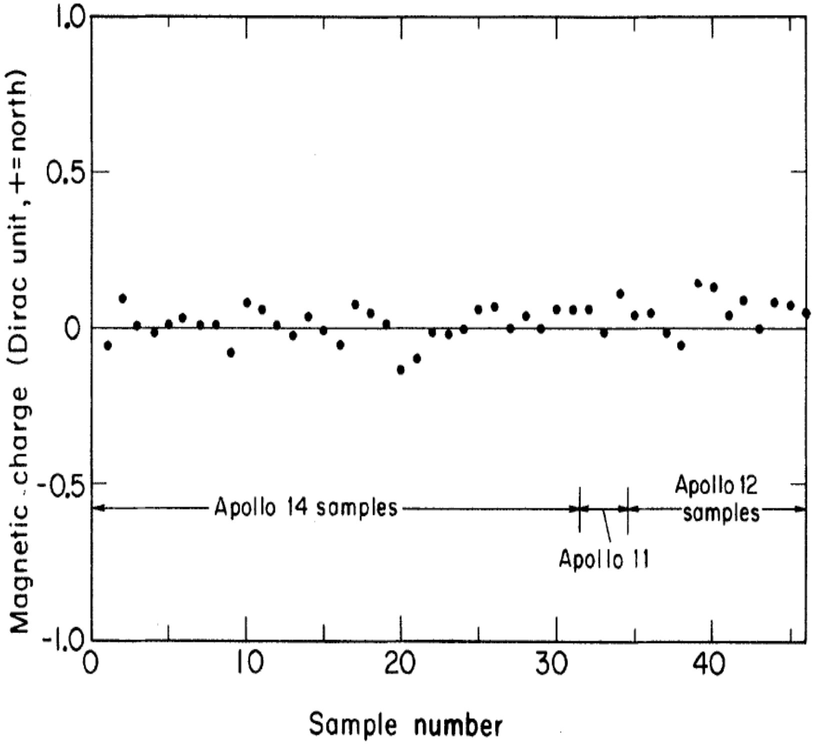
- Directly proportional to magnetic charge
- No mass dependence, no assumption on energy loss

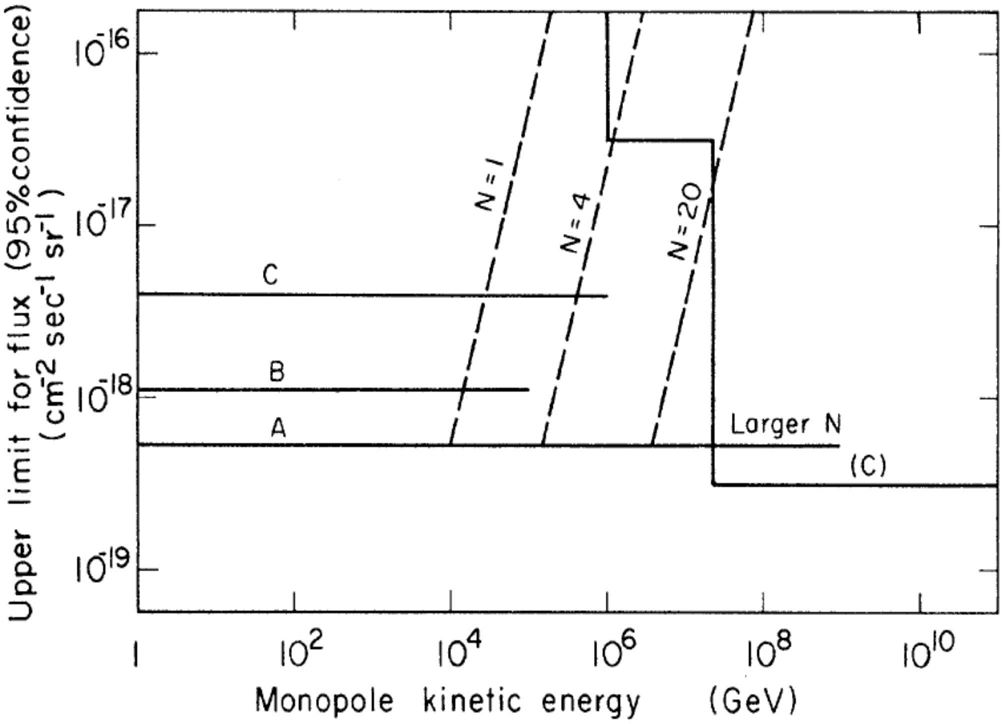


Moon rocks (induction)

- Used 47.8 kg of rocks returned from Apollo missions
- Exposure: 4 billions years!
  - No movement (few meters depth)
- No atmosphere and no magnetic field
  - Robust assessment of monopole fate after stopping

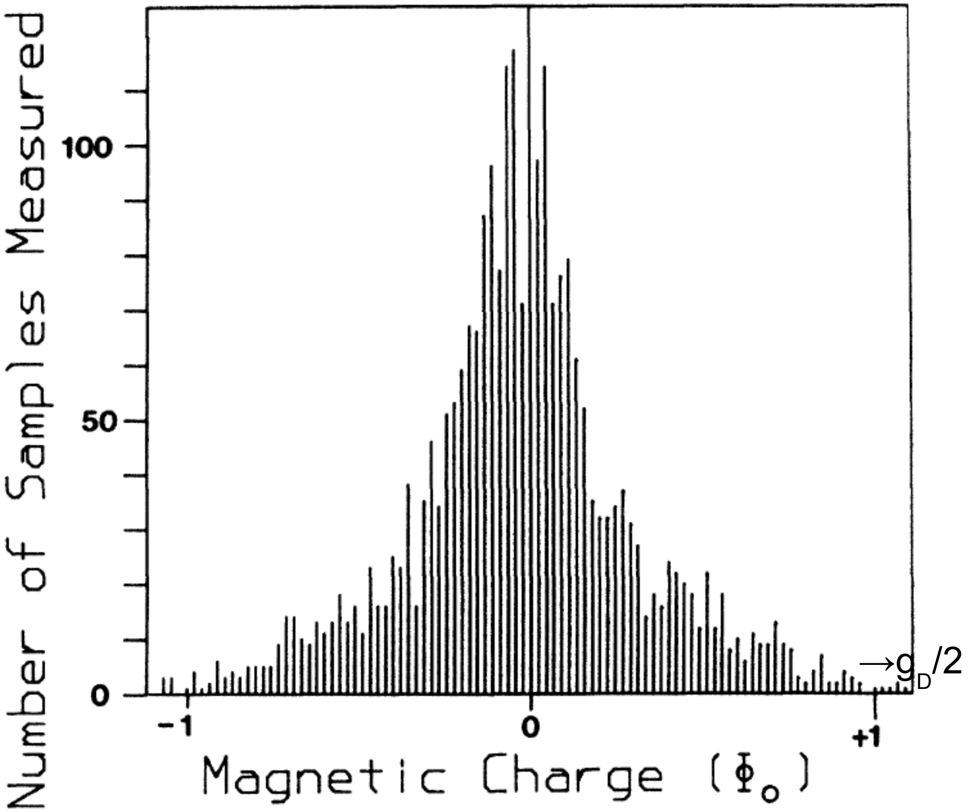
PRD 4, 3260 (1971)
PRD 8, 698 (1973)





Large-scale search with materials from Earth's crust (induction)

- 180 kg sea water
- 145 kg manganese nodules
- 498 kg deep schist
  depths of up to 25 km
  → stop higher-energy monopoles
- 20 times more material than all previous searches together
- Robust technique



PRA 33, 1183 (1986)

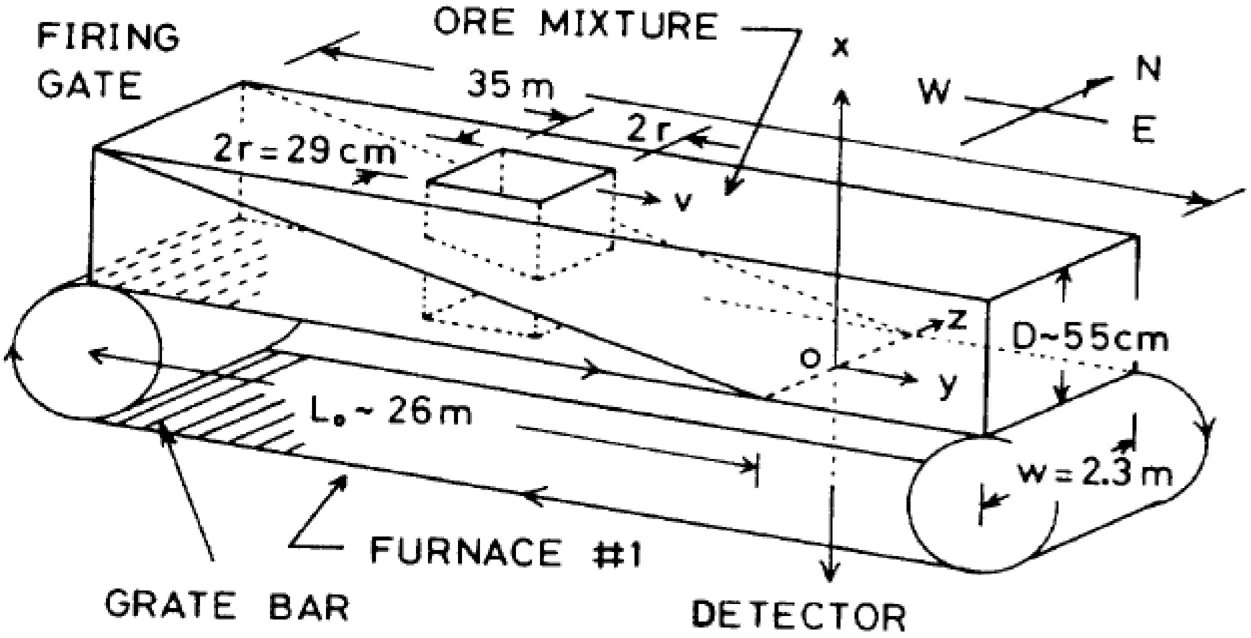
Iron ore (induction)

Superconducting coil placed under a furnace where iron ore Is heated to 1300 ^{0}C

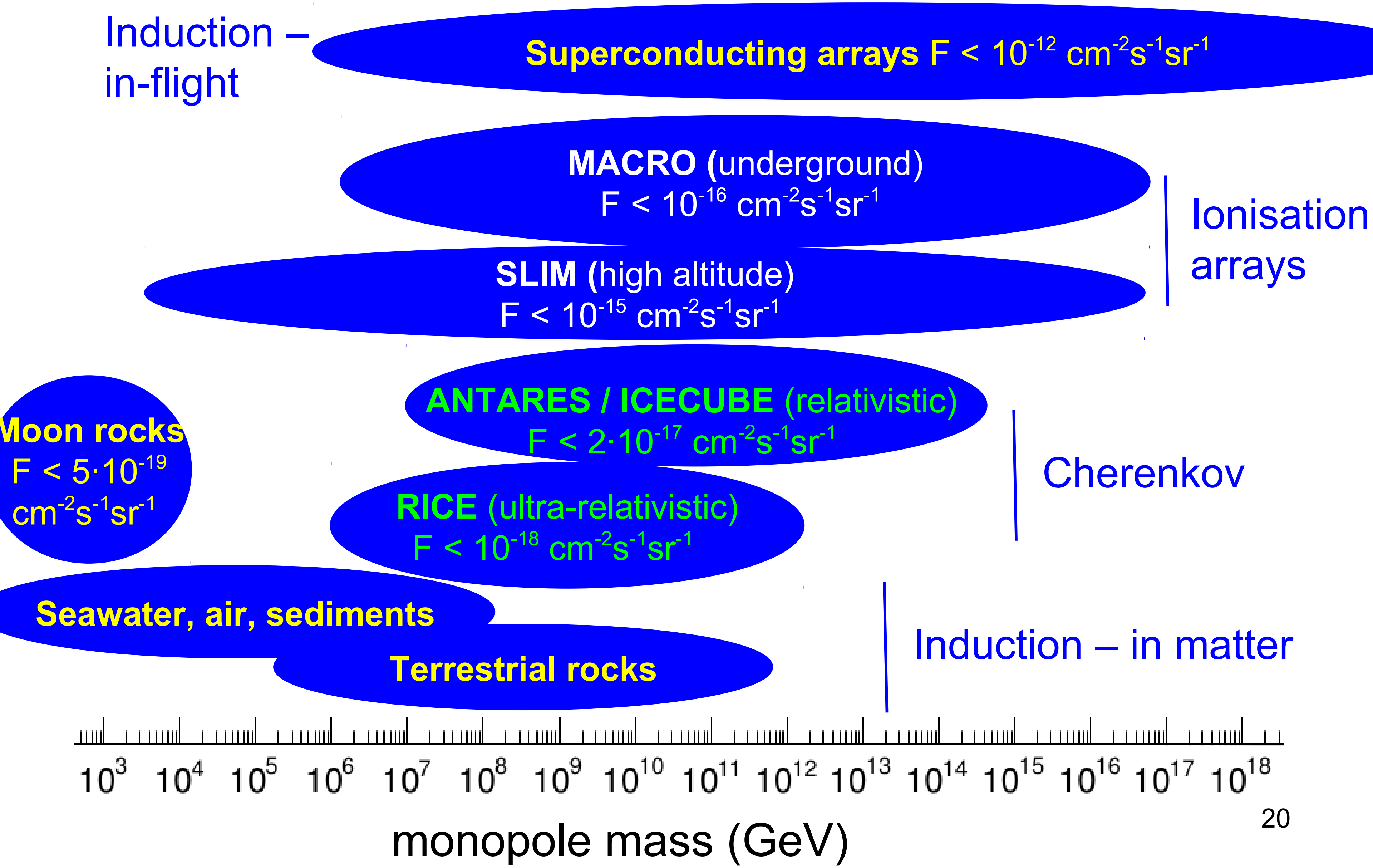
- Large amounts (>100 tons) of material
- Assume ferromagnetic binding

Must also assume no binding to nuclei!

PRD 36, 3359 (1987)



Cosmic monopole searches: flux limits



Induction – in-flight

Superconducting arrays F < 10^{-12} cm^{-2}s^{-1}sr^{-1}

MACRO (underground)
F < 10^{-16} cm^{-2}s^{-1}sr^{-1}

SLIM (high altitude)
F < 10^{-15} cm^{-2}s^{-1}sr^{-1}

Ionisation arrays

ANTARES / ICECUBE (relativistic)
F < $2{\cdot}10^{-17}$ cm^{-2}s^{-1}sr^{-1}

RICE (ultra-relativistic)
F < 10^{-18} cm^{-2}s^{-1}sr^{-1}

Cherenkov

Moon rocks
F < $5{\cdot}10^{-19}$
cm^{-2}s^{-1}sr^{-1}

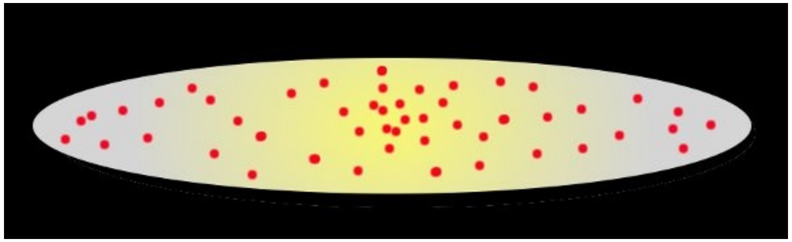
Seawater, air, sediments

Terrestrial rocks

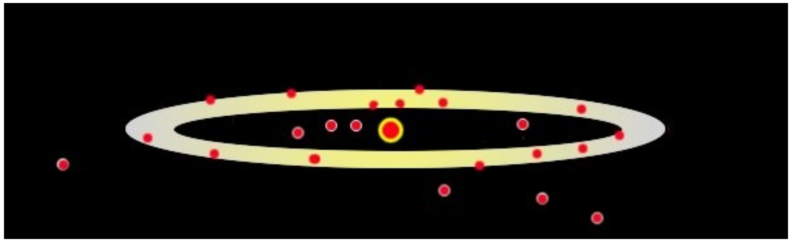
Induction – in matter

Stellar monopoles – where should they be?

Cloud

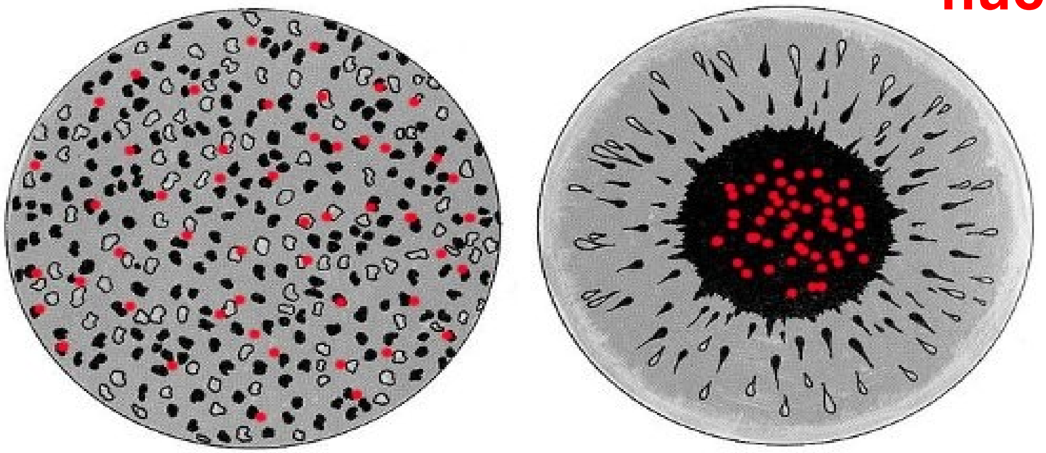


Planetary System



Monopoles are (much) heavier than the heaviest nuclei

Planetary differentiation



Stellar monopoles – where should they be?

- Essentially absent from planetary crusts
- Searches in water, air, sediments, rocks, moon rocks... are not sensitive to stellar monopoles

Possibly:

- Inside the Sun
- In asteroids and comets → meteorites
- Inside the cores of planetary bodies

Indirect limit on stellar monopoles in Earth

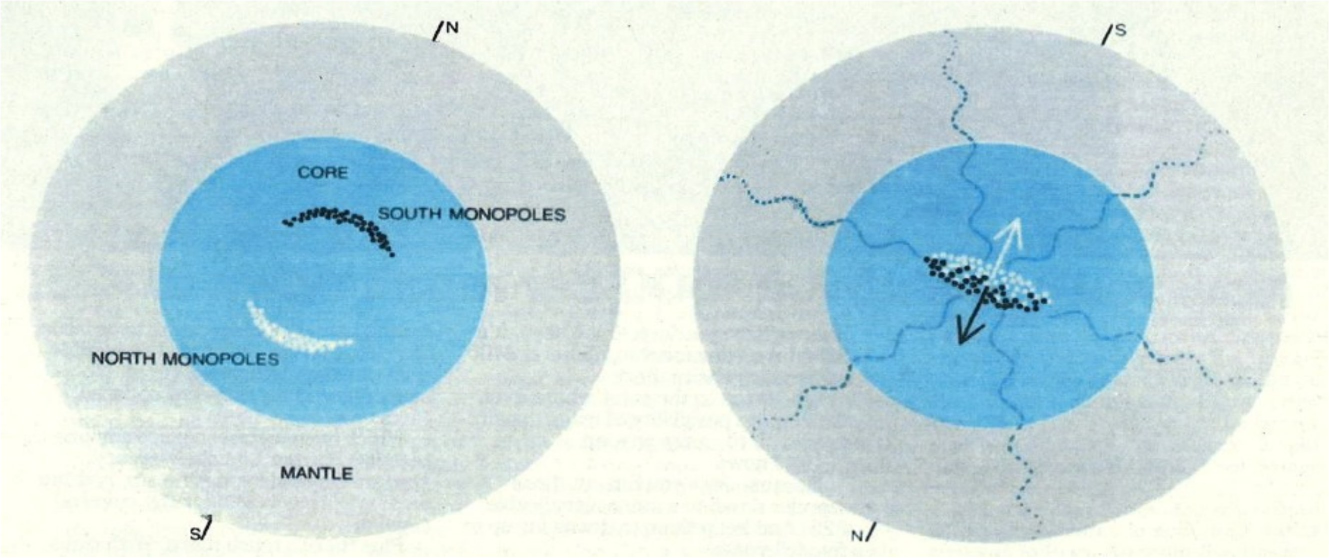
Expect heat generation from monopole-antimonopole annihilations during geomagnetic reversals

→ limit $\rho < 10^{-28}$ monopoles/nucleon

Nature 288, 348 (1980)

Must assume mass 10^{16} GeV and:

- Stable dipole magnetic field when no reversal
- Monopoles and anti-monopoles both present



Indirect limit on stellar monopoles in Moon

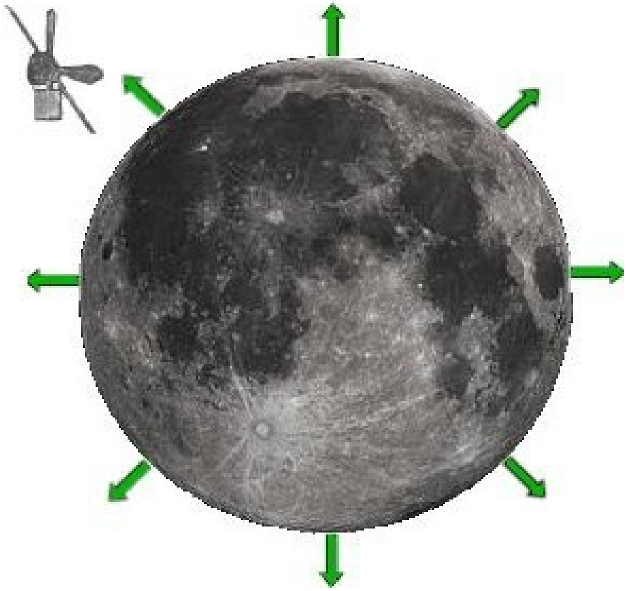
Magnetometer observations aboard Explorer 35 orbiting the Moon

→ limit $\rho < 10^{-32}$ monopoles/nucleon

Must assume:

Phys. Rev. D 27, 1525 (1983)

- Moon does not originate from Earth's crust
- Monopoles predominantly of one sign



Search in meteorites (induction)

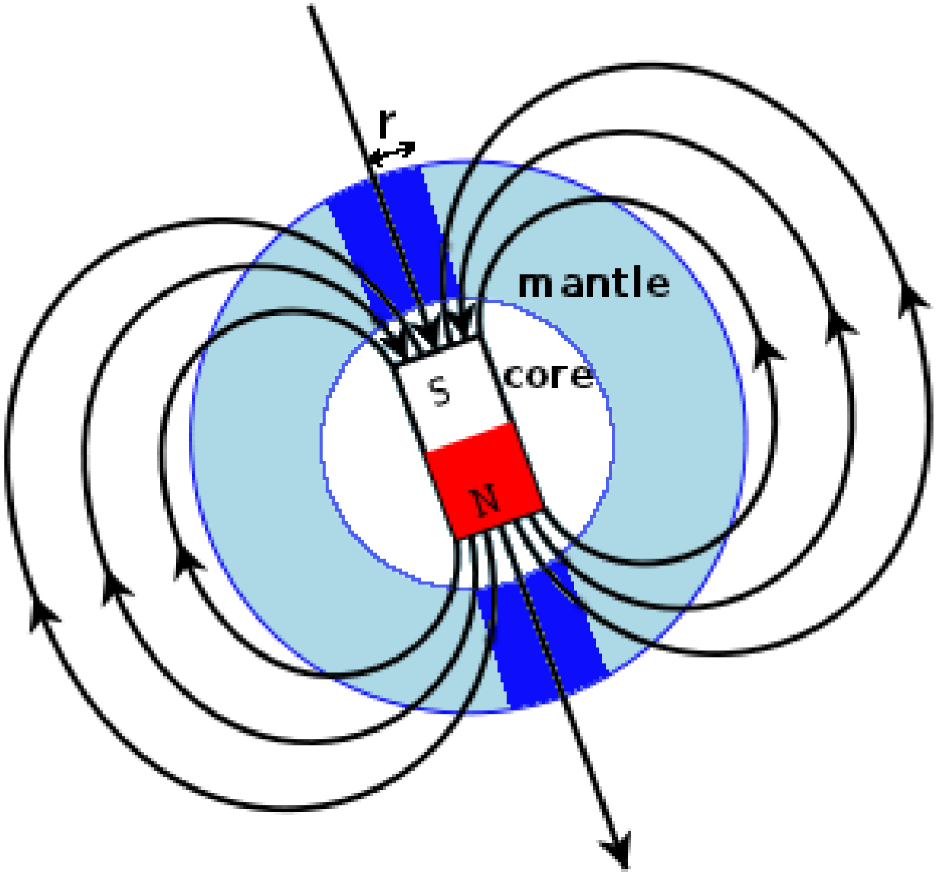
Phys. Rev. Lett. 75, 1443 (1995)

- Probed a total of 331 kg of rocks (meteorites, ferromanganese nodules, iron ores, blueschists, sediments, kimberlites, chromates)
- 112 kg of meteorites
  - ~100 kg are chondrites, believed to derive directly from primary solar nebula
    → stellar monopoles!
  - Masses up to 10^{17} GeV, beyond which monopoles might be dislodged by meteor impact

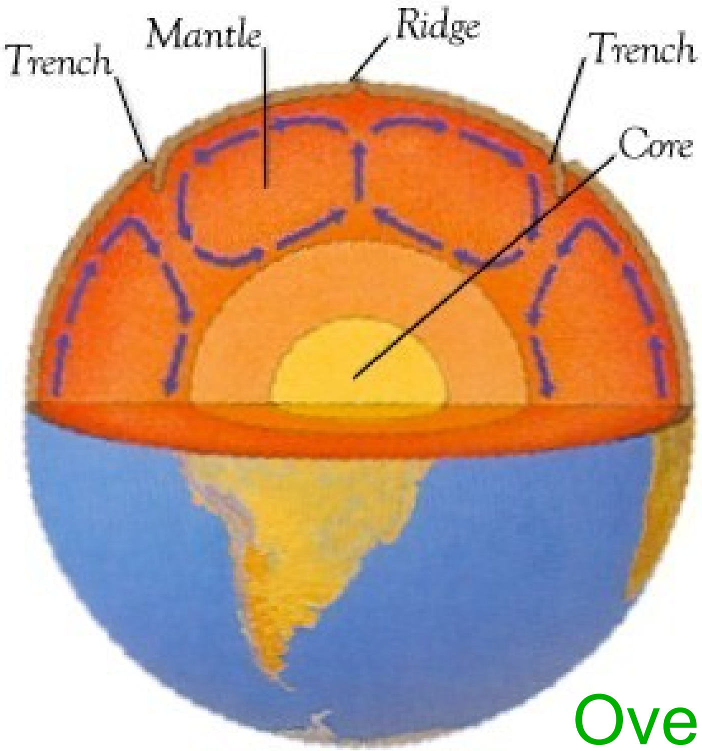
Search in polar volcanic rocks (induction)

Recent idea:

Monopoles inside the Earth could migrate along magnetic axis all the way up to the surface



Dynamics of monopoles with equilibrium position inside the mantle

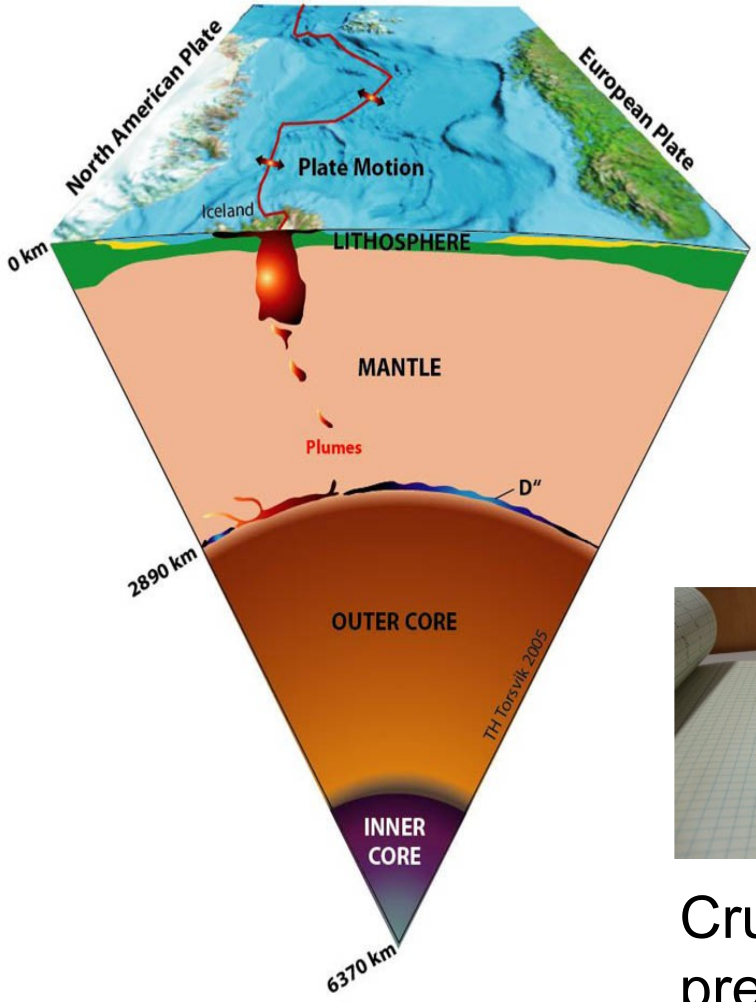


For Dirac charge ($n = 1$), magnetic force exceeds gravitational force above core-mantle boundary for: $m < 4 \cdot 10^{14}$ GeV

→ monopole follows mantle convection and mantle plumes

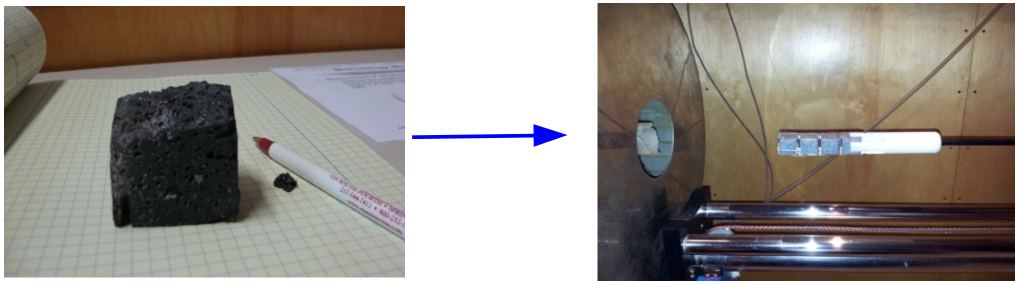
Over geologic time, accumulation in the mantle beneath the geomagnetic poles for a wide range of masses and charges

Polar volcanic rock search – samples



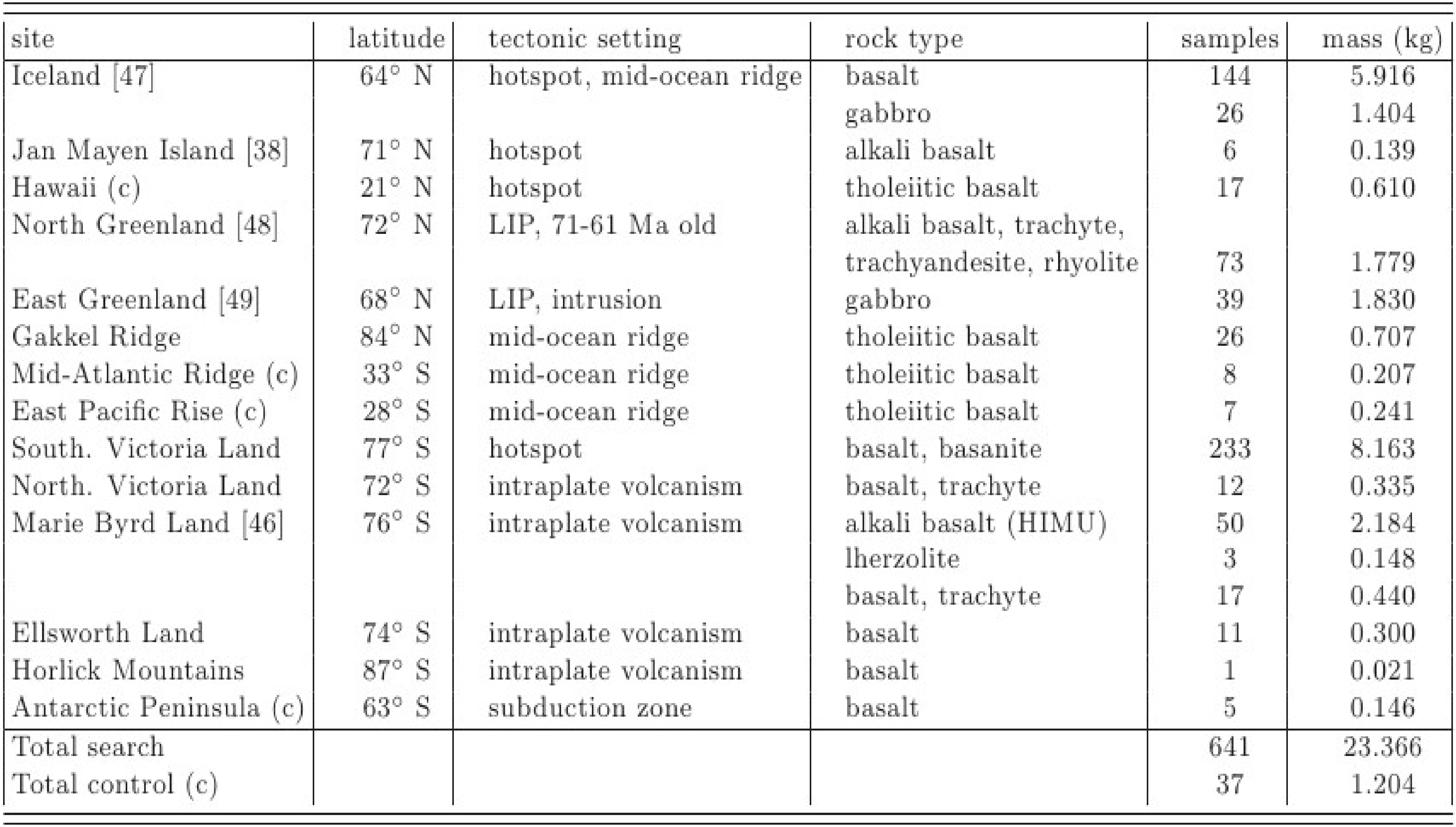
High latitude (>63^0), mantle derived

- Hotspots
- Mid-ocean ridges
- Large igneous provinces
- Isotopic content indicating deep origins



Crushed to reduce magnetisation for precise magnetometer measurement

Polar volcanic rock search – samples



site	latitude	tectonic setting	rock type	samples	mass (kg)
Iceland [47]	64° N	hotspot, mid-ocean ridge	basalt	144	5.916
			gabbro	26	1.404
Jan Mayen Island [38]	71° N	hotspot	alkali basalt	6	0.139
Hawaii (c)	21° N	hotspot	tholeiitic basalt	17	0.610
North Greenland [48]	72° N	LIP, 71-61 Ma old	alkali basalt, trachyte, trachyandesite, rhyolite	73	1.779
East Greenland [49]	68° N	LIP, intrusion	gabbro	39	1.830
Gakkel Ridge	84° N	mid-ocean ridge	tholeiitic basalt	26	0.707
Mid-Atlantic Ridge (c)	33° S	mid-ocean ridge	tholeiitic basalt	8	0.207
East Pacific Rise (c)	28° S	mid-ocean ridge	tholeiitic basalt	7	0.241
South. Victoria Land	77° S	hotspot	basalt, basanite	233	8.163
North. Victoria Land	72° S	intraplate volcanism	basalt, trachyte	12	0.335
Marie Byrd Land [46]	76° S	intraplate volcanism	alkali basalt (HIMU)	50	2.184
			lherzolite	3	0.148
			basalt, trachyte	17	0.440
Ellsworth Land	74° S	intraplate volcanism	basalt	11	0.300
Horlick Mountains	87° S	intraplate volcanism	basalt	1	0.021
Antarctic Peninsula (c)	63° S	subduction zone	basalt	5	0.146
Total search				641	23.366
Total control (c)				37	1.204

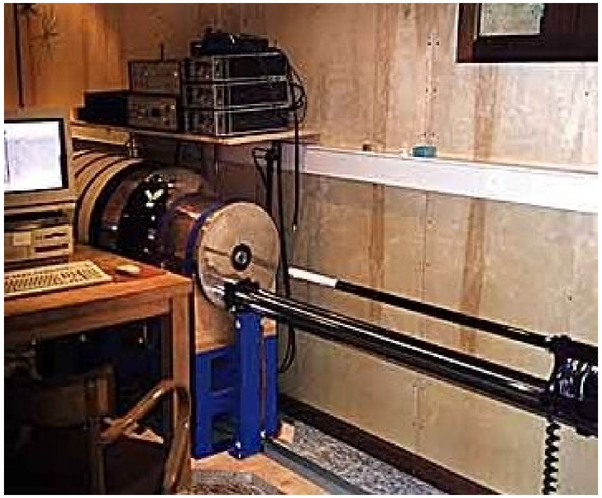
Phys. Rev. Lett. 110, 121803 (2013)

Magnetometer tests for trapped monopoles searches (1)

Laboratory of Natural Magnetism, ETH Zurich

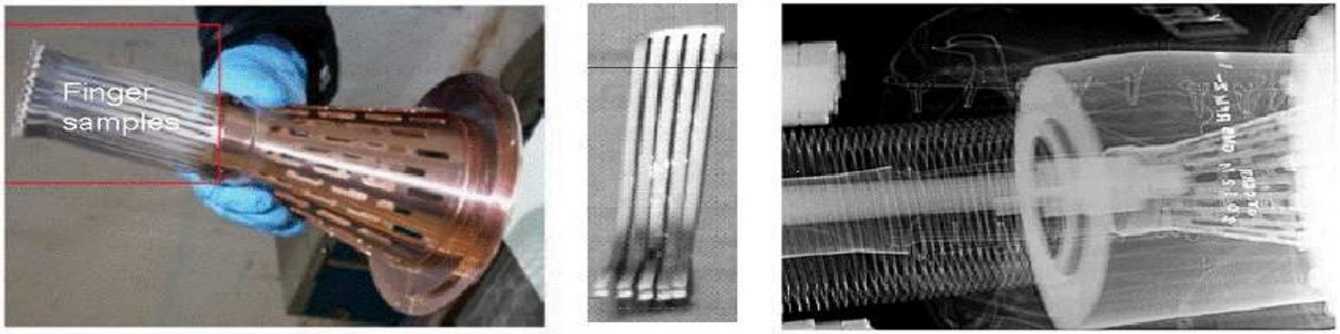
Magnetically shielded room

DC-SQUID magnetometer



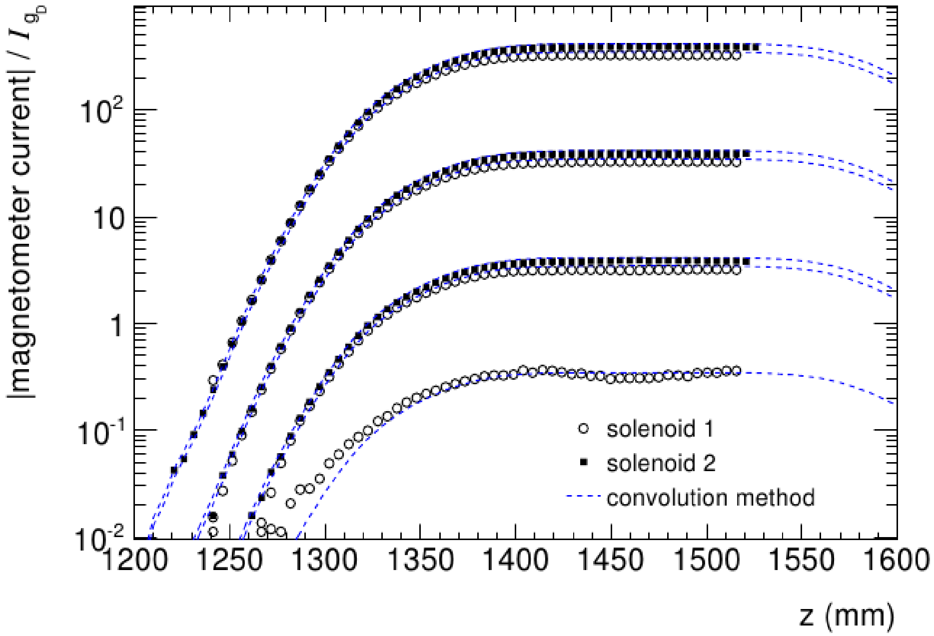
Magnetometer tests for trapped monopoles searches (2)

Proof-of-principle using accelerator material near CMS

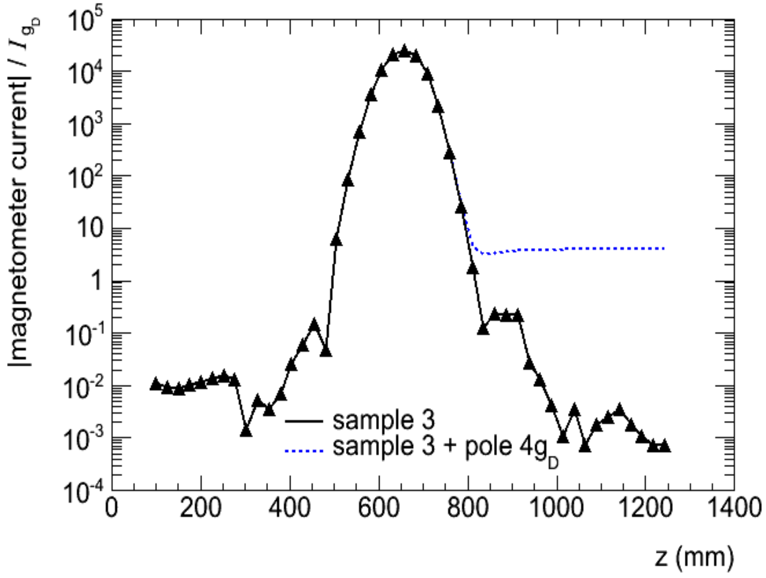


X-ray image of defective plug-in module

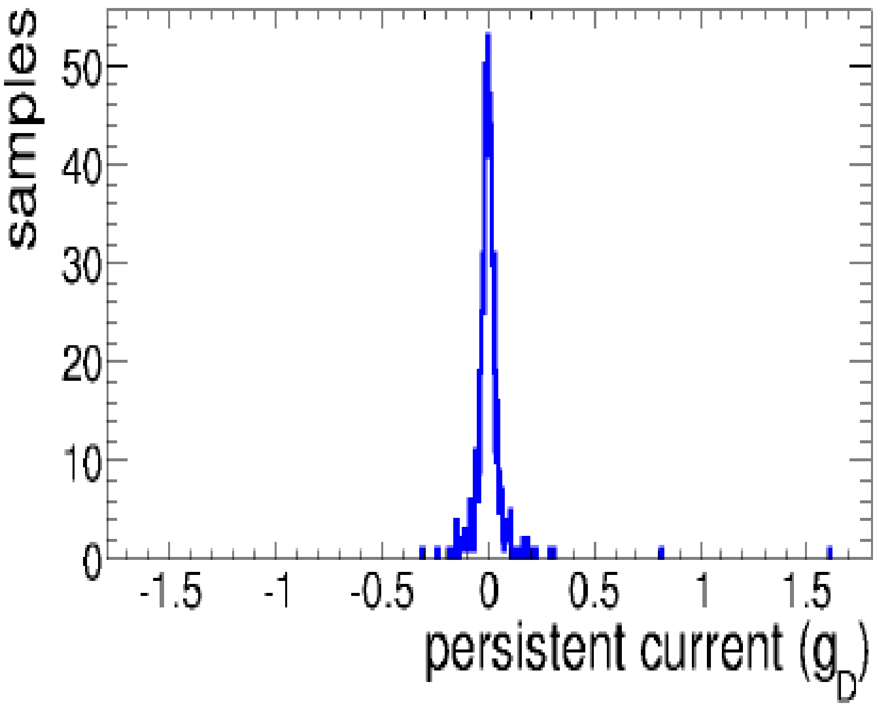
Calibration cross-check with long, thin solenoids

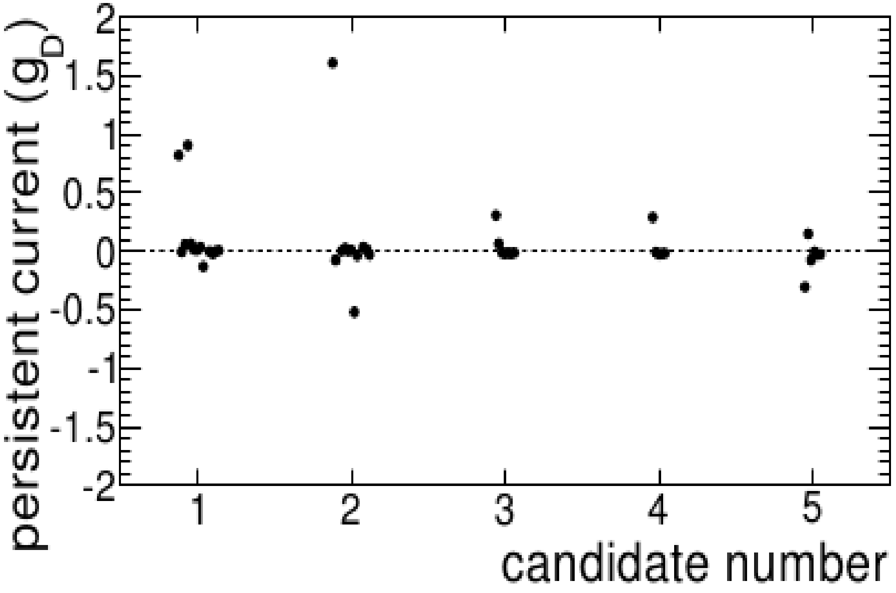


Eur. Phys. J. C 72, 2212 (2012)



Polar volcanic rock search – results

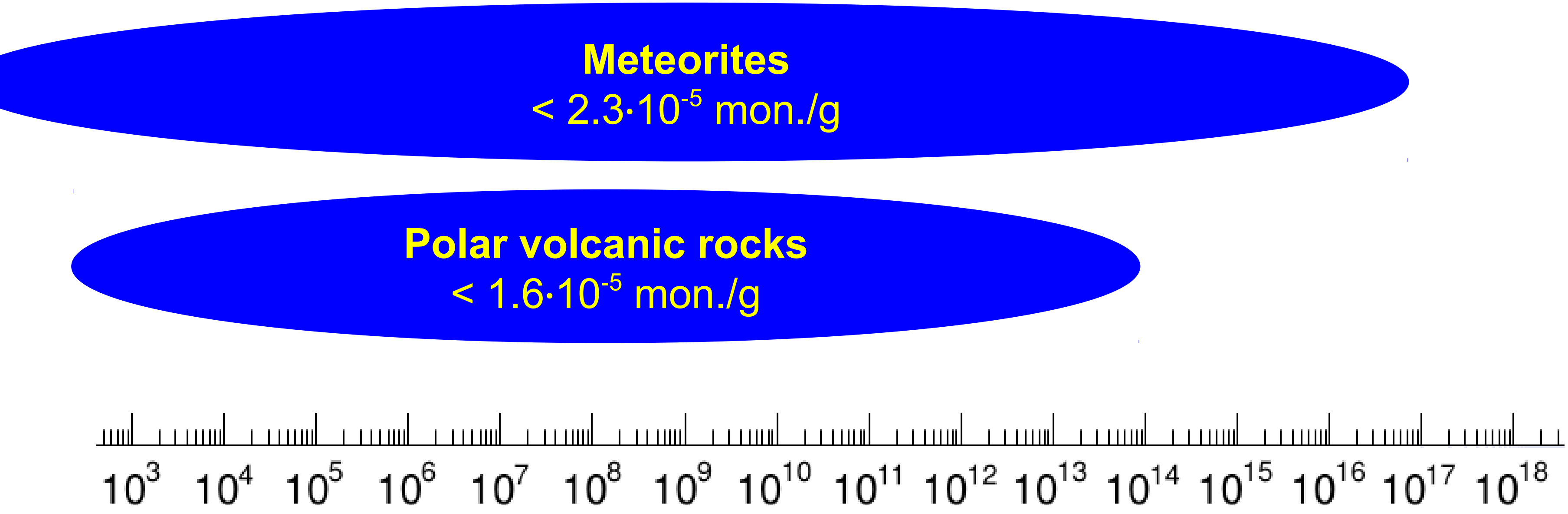




Phys. Rev. Lett. 110, 121803 (2013)

- No monopoles found in 24 kg of polar volcanic rocks
  - In simple model, translates into limit of less than 0.02 monopole per kg in the Solar System (90% c.l.)
- Comparable and complementary to meteorite search

Direct stellar monopole searches: limits on monopole density in the Solar System



Meteorites
< $2.3 \cdot 10^{-5}$ mon./g

Polar volcanic rocks
< $1.6 \cdot 10^{-5}$ mon./g

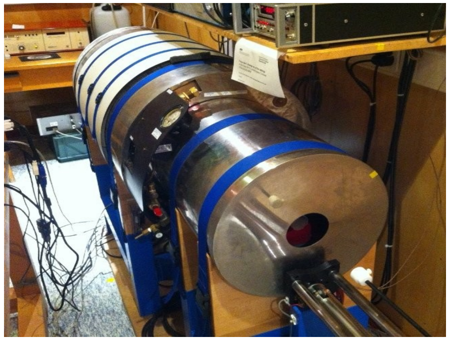
Monopoles at the LHC

Higher collision energies than ever before!

  - Can probe higher monopole masses, up to several TeV

- General-purpose detectors (ATLAS)
- Dedicated monopole detector (MoEDAL)
- Trapping experiments

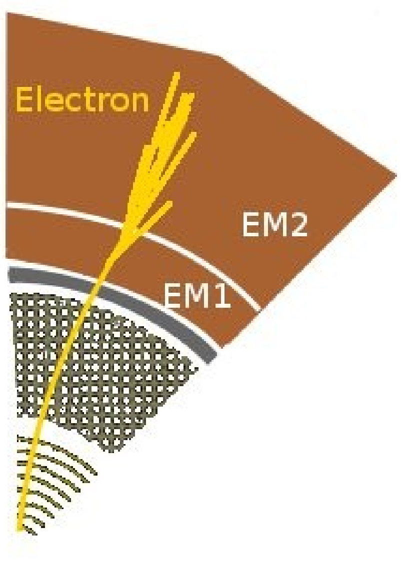
Large Hadron Collider, Geneva

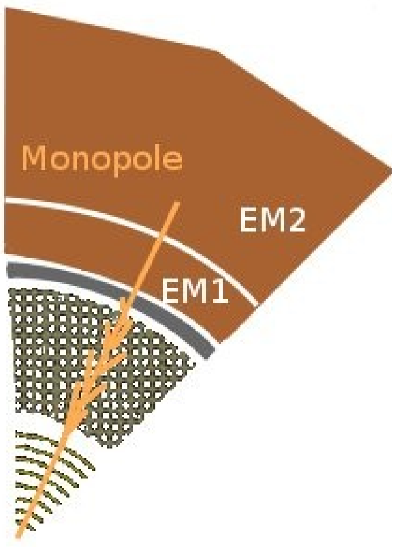


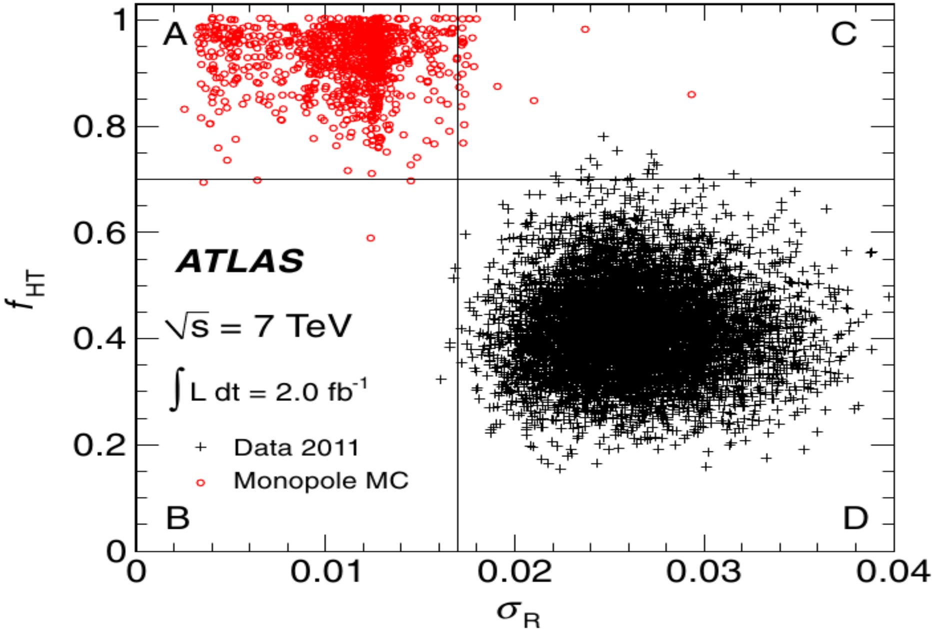
SQUID magnetometer, Zurich

ATLAS monopole search

PRL 109, 261803 (2012), arXiv:1207.6411





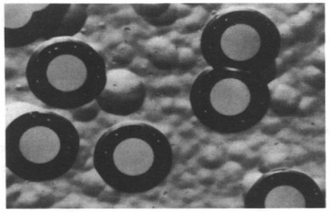


- **Signature:** high ionisation hits and narrow energy deposition
- Special simulation of monopole energy loss and trajectory in magnetic field
- Recently developed new event trigger for better sensitivity
    - Monopole still needs to reach EM calorimeter

The MoEDAL experiment

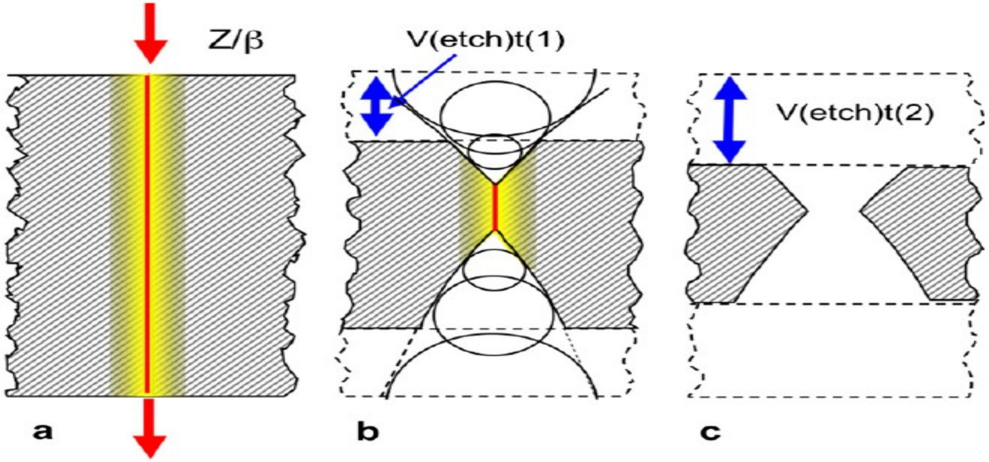
Dedicated to highly-ionising particle detection

Principle: passive detectors are exposed to collision products around LHCb collision point



Main detector:

- Thin plastic foils
- High ionisation signature
- Track-etch technique

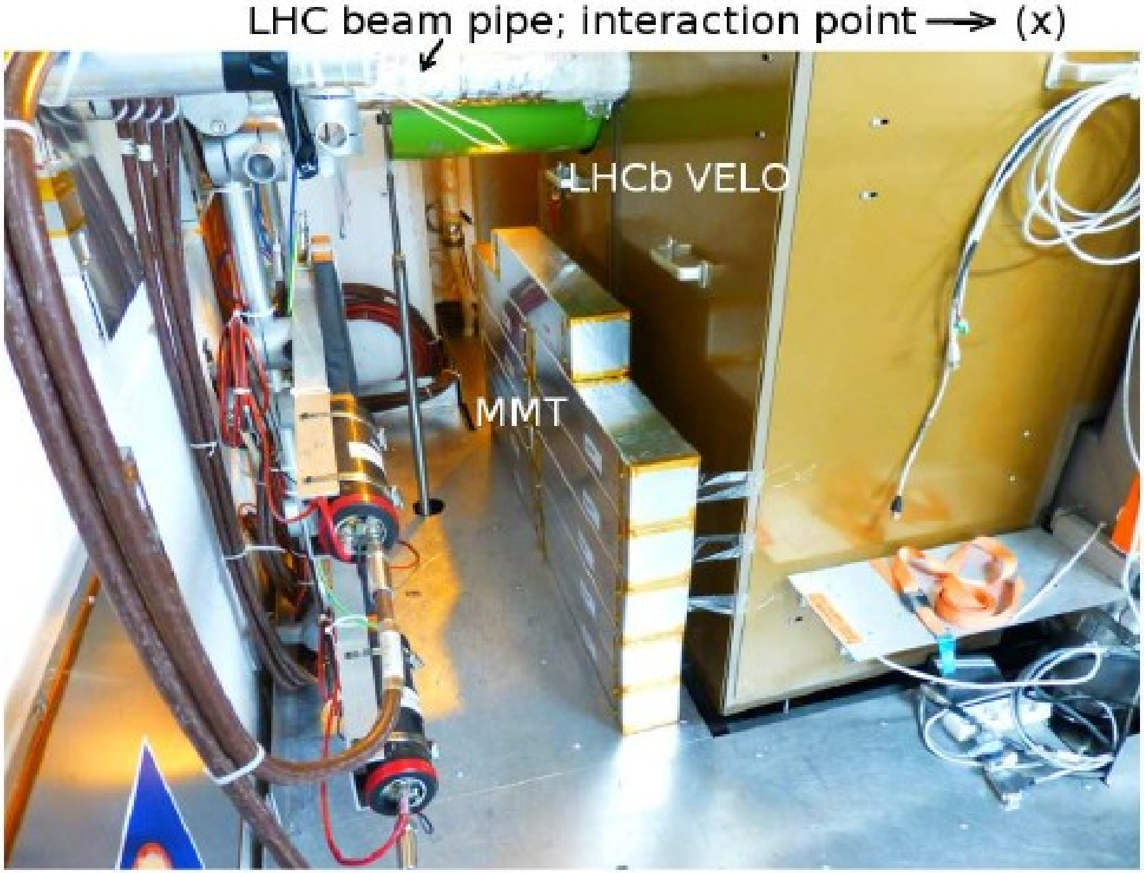


New subdetector:

- Mag. monopole trapper (MMT)
- Aluminium absorber
- Induction technique

MoEDAL – status

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



Test arrays deployed in 2012

Main run planned for 2015

Trapped monopoles at the LHC (induction)

Ongoing project:

Search in dedicated aluminium trapping volume (MoEDAL MMT)

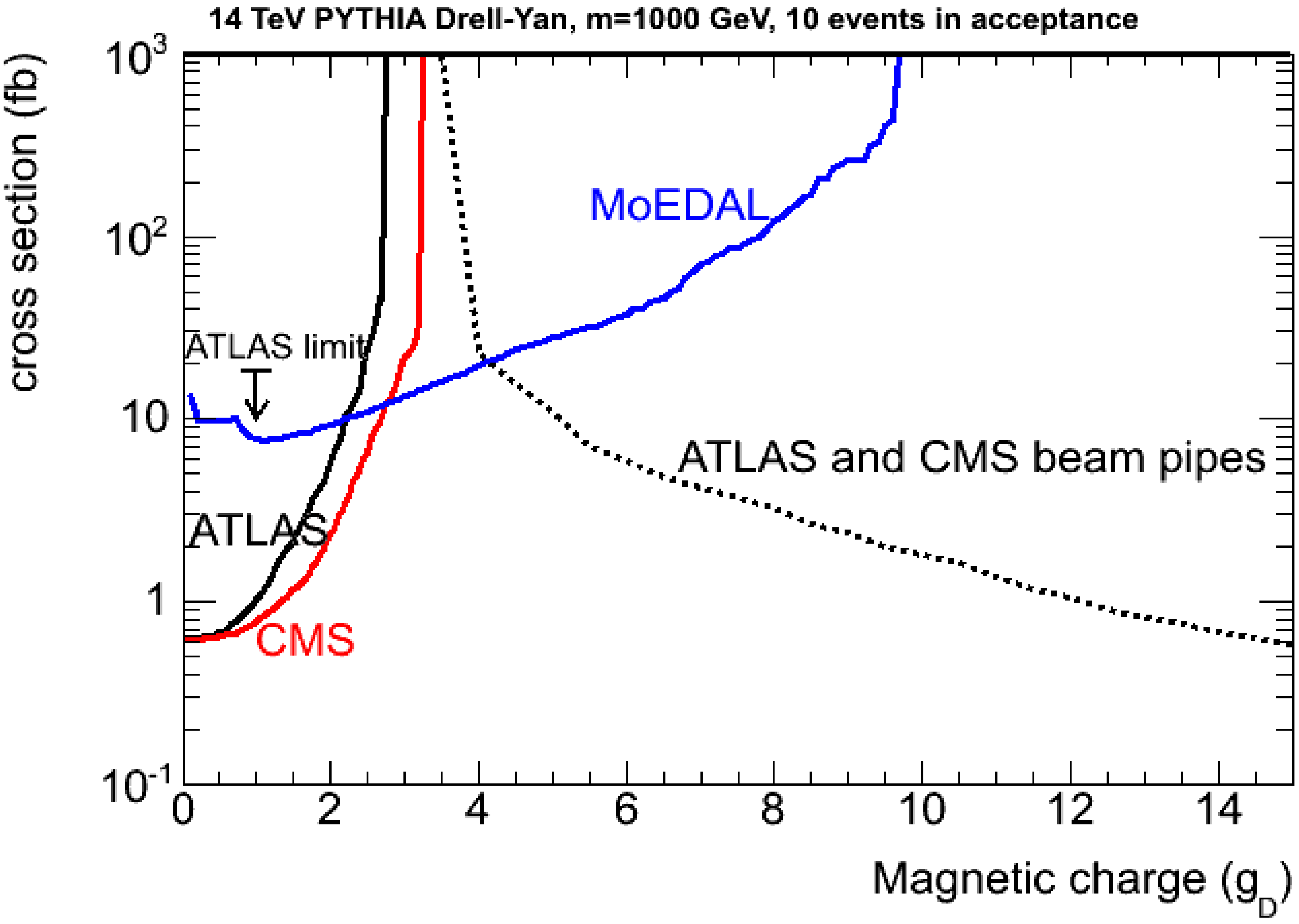
Future proposal:

Search in ATLAS and CMS beryllium beam pipes

- Being replaced this year
- Only vacuum between interaction point and beam pipe
  → **sensitivity to very high magnetic charges ($n > 4$)**

Monopoles at the LHC: Summary

Cross section needed for 10 events in acceptance after one year of LHC running



A. De Roeck *et al.*, EPJC 72, 1985 (2012), arXiv:1112.2999

Summary

Magnetic monopoles are fundamental, well-motivated objects

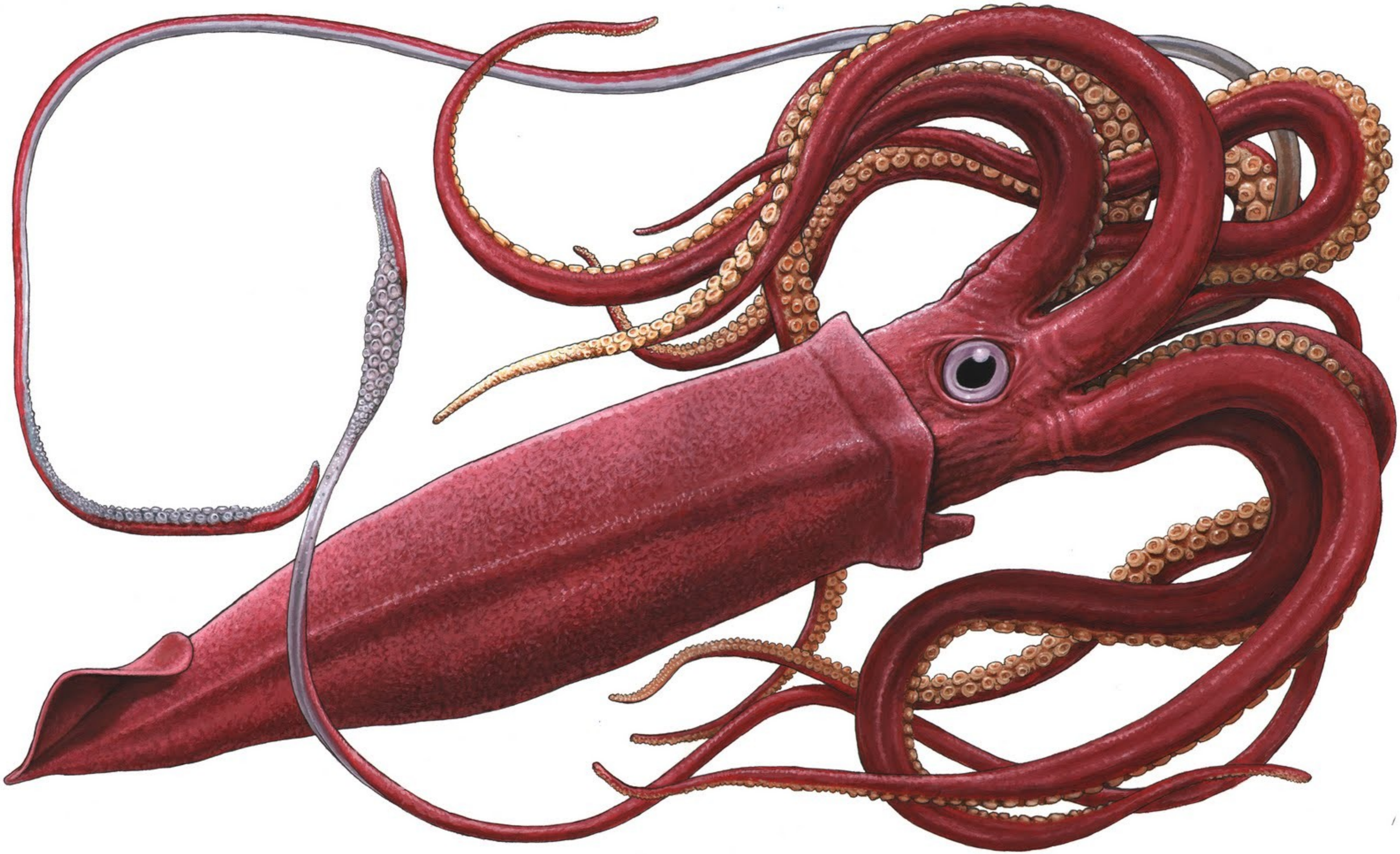
- Past searches excluded the existence of secondary monopoles produced in cosmic-ray and accelerator collisions
  - Still probing higher masses at the LHC

Beyond the TeV scale, primordial monopoles are allowed to take mass values up to the Planck scale

- So far, no such monopoles were seen as a cosmic-ray component or a component of matter
  - Very rare? → probe larger amounts of material
  - Hiding? → probe more exotic stuff, e.g. asteroid cores, cometary dust...

To catch the monopole, perhaps what we need is...

To catch the monopole, perhaps what we need is...



A giant SQUID!

Extra slides

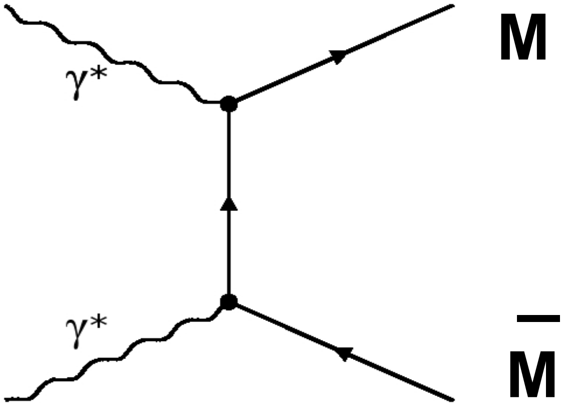
Property: production

EM coupling constant for Dirac charge = 34.25

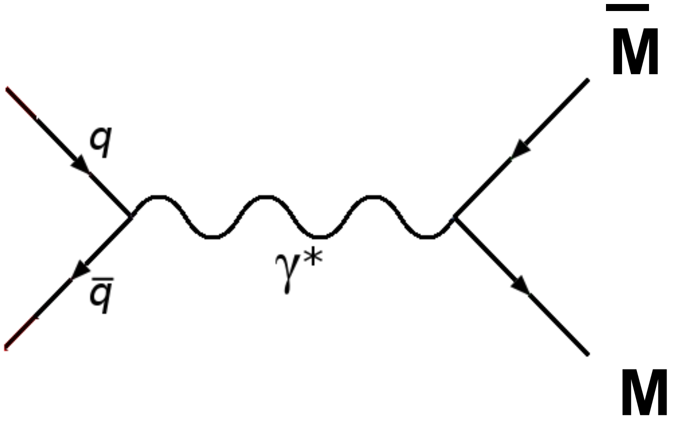
→ non-perturbative dynamics, no reliable cross sections and kinematics!

<u>“Natural” benchmark models:</u>

photon fusion



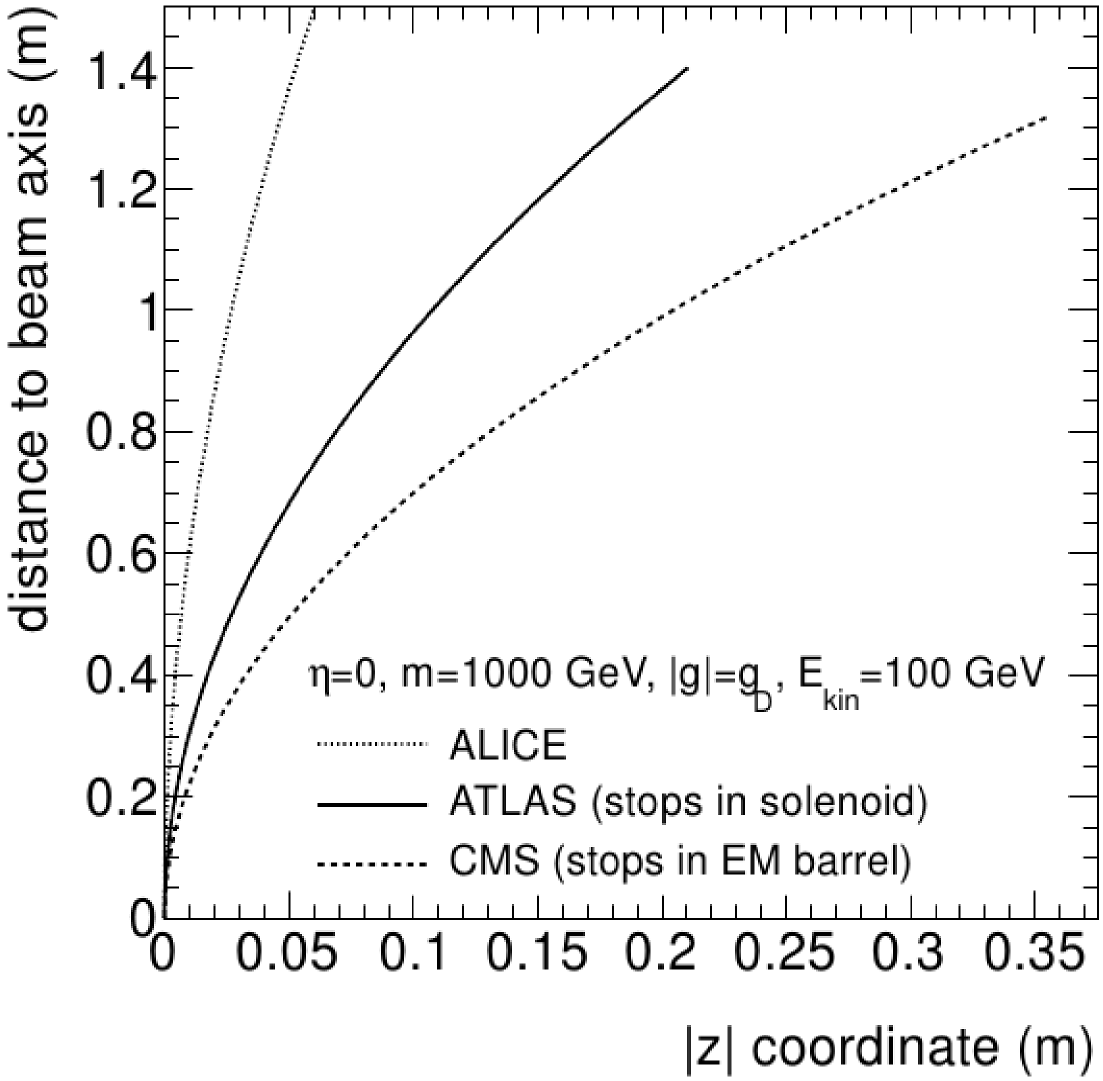
Drell-Yan



<u>Remark</u>: magnetic charge conservation prescribes that monopoles are **stable** and **produced in pairs**

Monopole bending

arXiv:1112.2999



Acceleration along magnetic field:

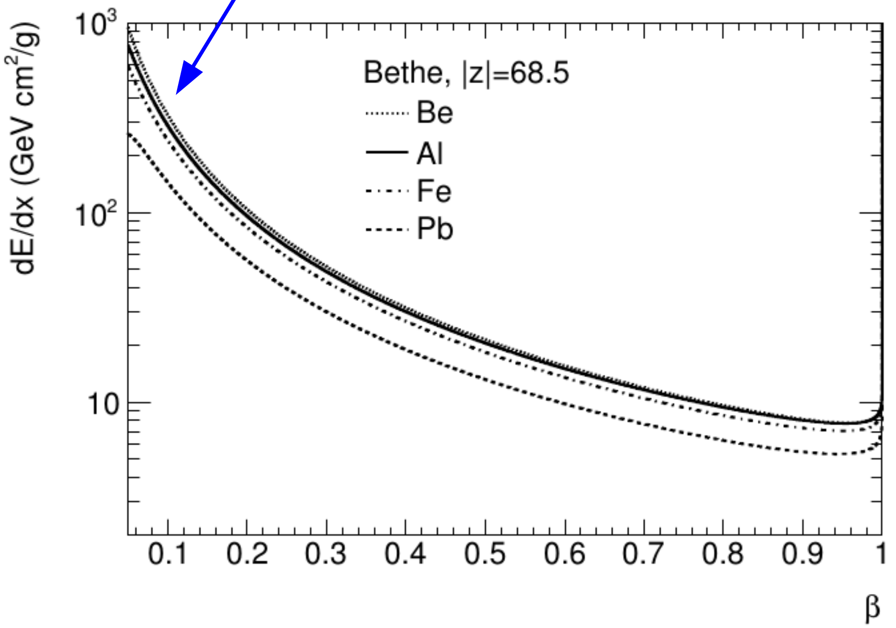
$$F_m = q_m \cdot B$$

- Straight line in *xy* plane
- Parabola in *rz* plane

Monopole ionisation energy loss

Electric

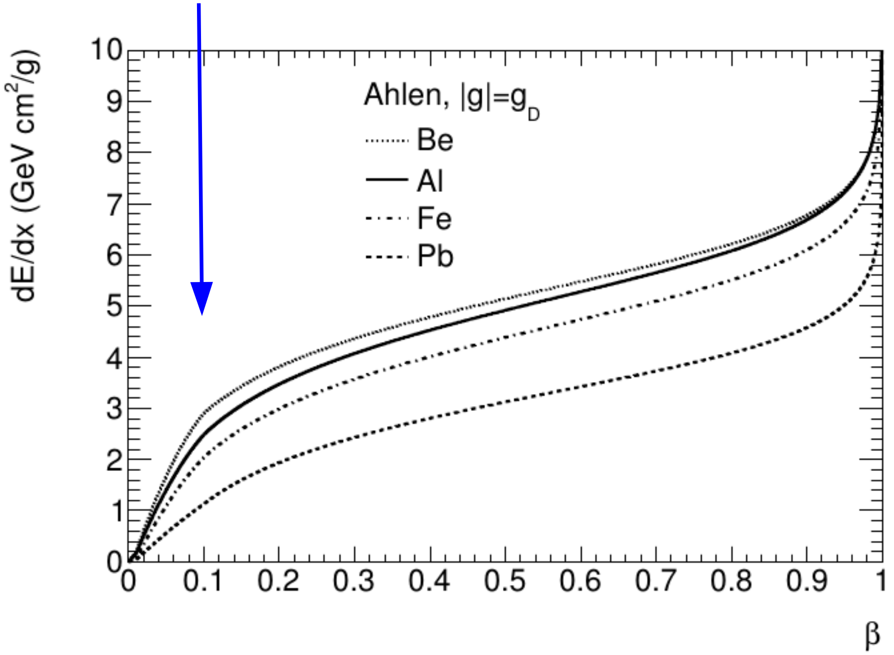
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2\right]$$



Magnetic

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

No Bragg peak!

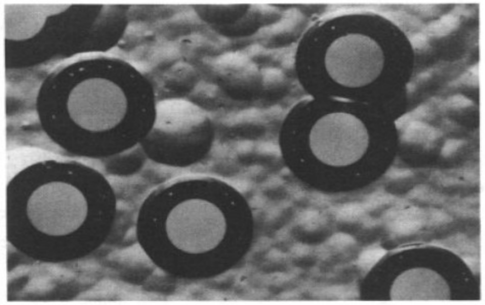


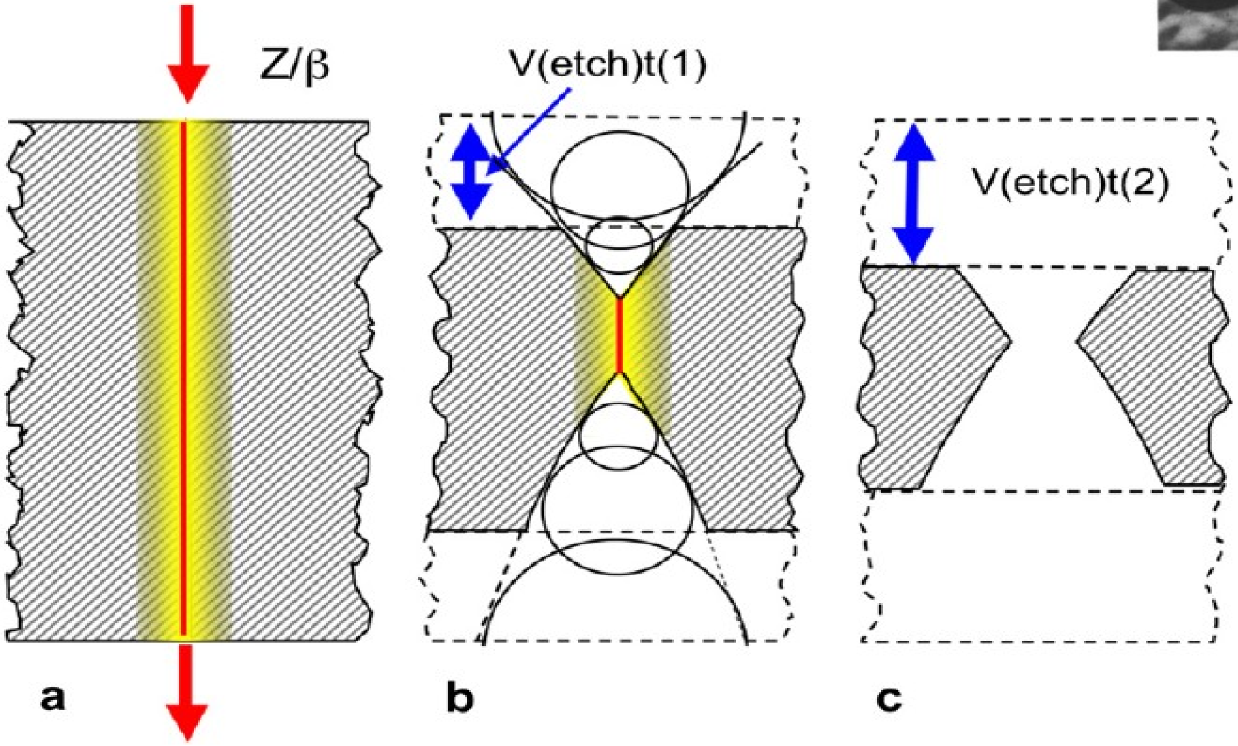
Dirac monopole: $|g_D| = 68.5$ → several thousand times greater d*E*/d*x* than a minimum-ionising |z|=1 particle

Detection: track-etch technique

Principle: passage of highly ionising particle causes permanent damage in plastic foils

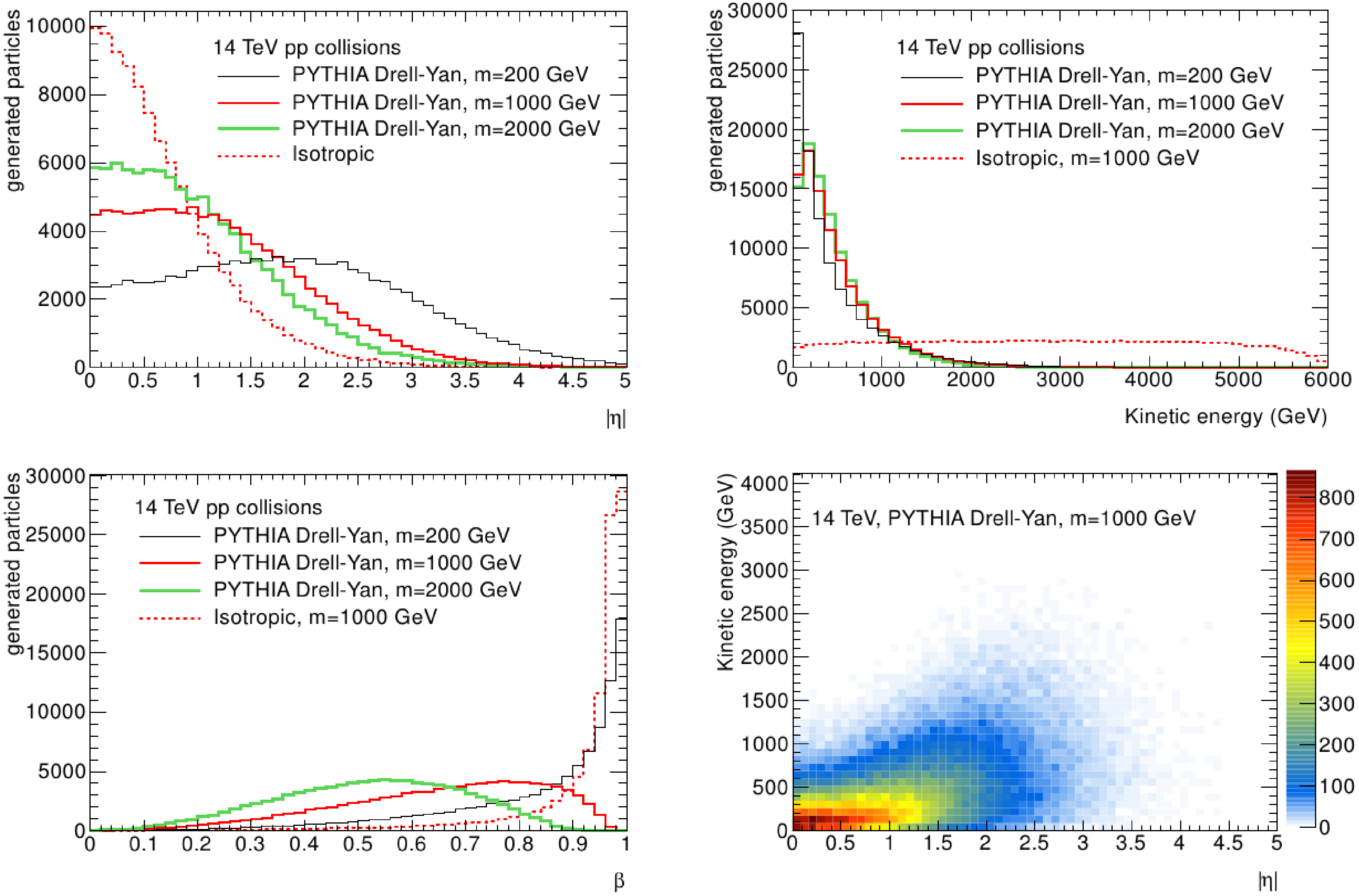
- Etching reveals the etch-pit cones
- Easily tested with ion beams





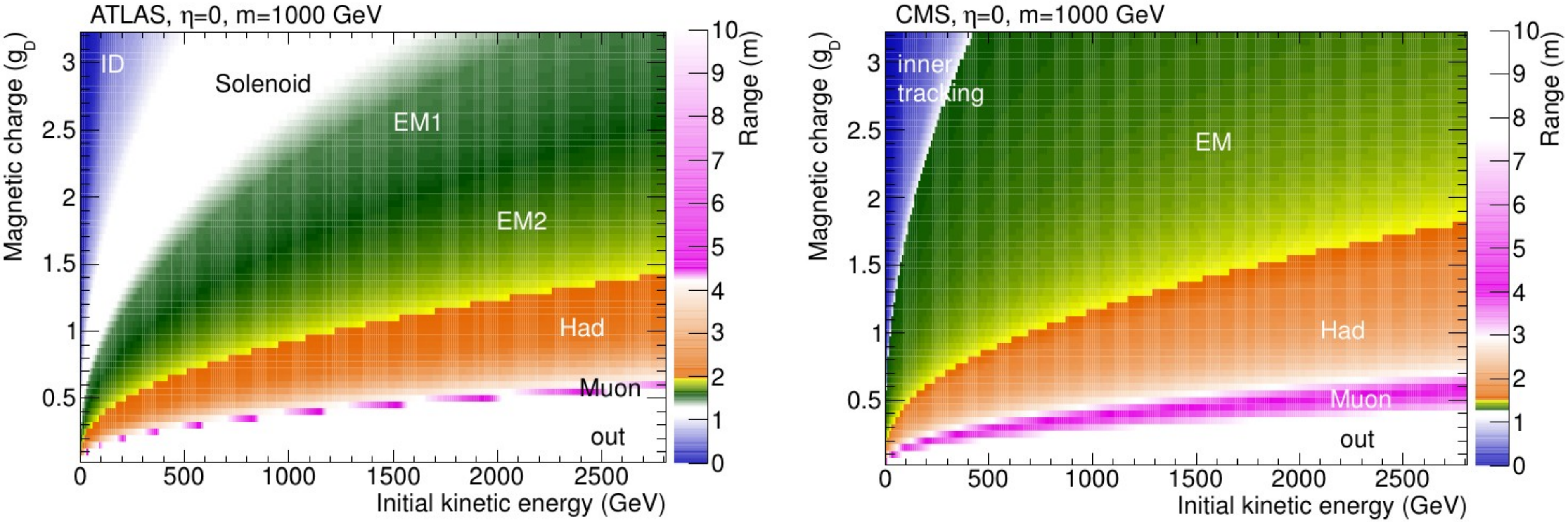
Monopole production kinematics

arXiv:1112.2999



Range of monopoles in ATLAS and CMS

arXiv:1112.2999 (2012)

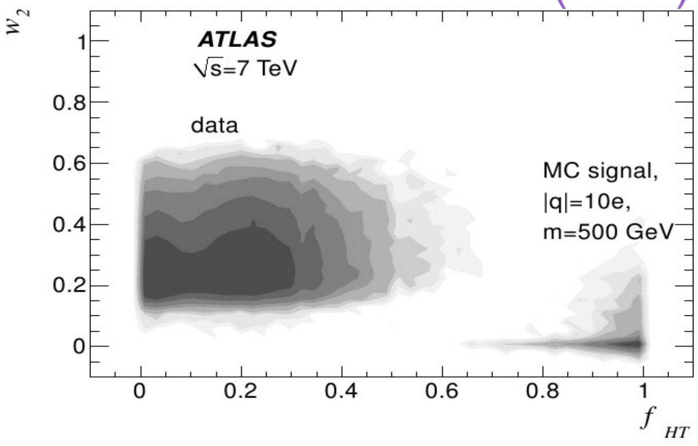


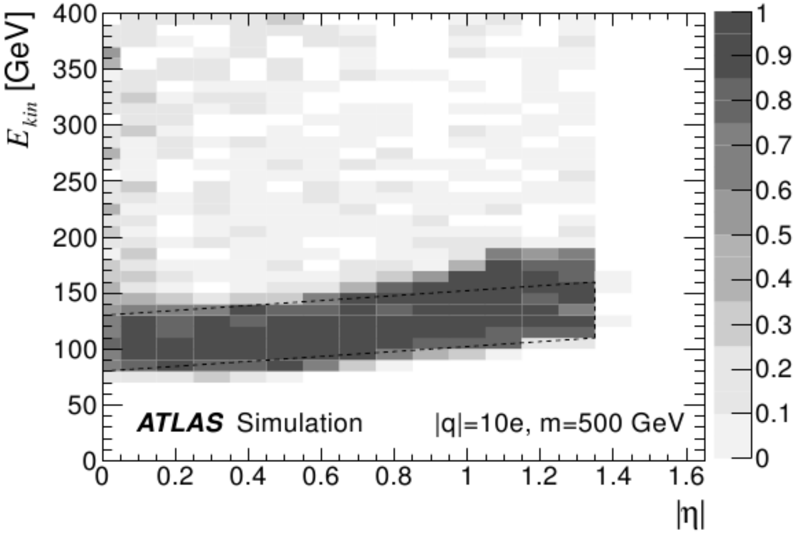
ATLAS search multiply-charged particles

First HIP search at the LHC

- Very first data (summer 2010)
- Standard EM trigger and reco
- Interpretation $6e < |q_e| < 17e$

arXiv:1102.0459 (2011)





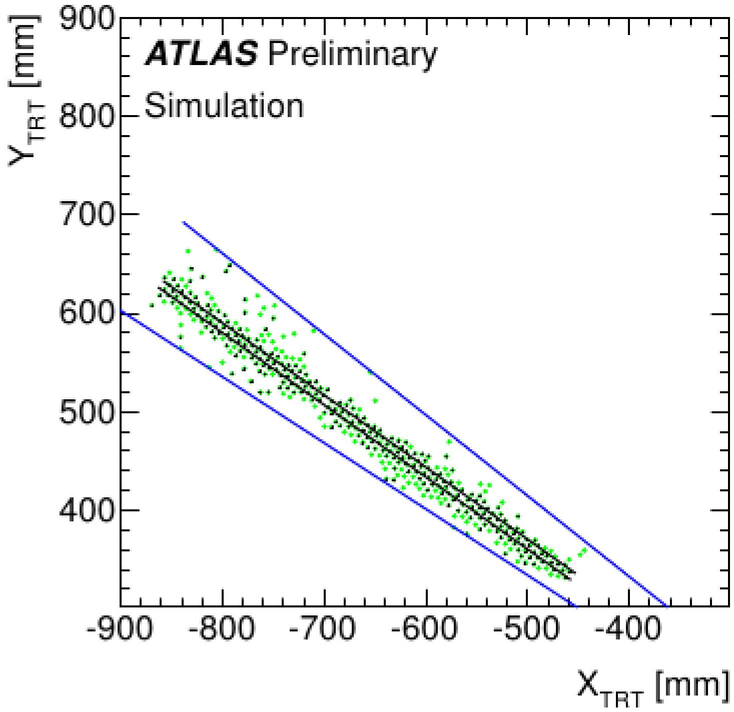
Major source of inefficiency comes from acceptance (punch through) → **Model-independent approach:** 1-2 pb limits set in well-defined kinematic ranges

Sequel: monopole search with 2011 data (next slides)

ATLAS monopole search – principle

- Data from 2011 (2 fb^{-1})
- Standard EM trigger
- Special tracking
  - Count TRT hits in window around EM cluster
  - Robust against delta-electrons and anomalous bending
- Signature: high-threshold TRT hits associated to narrow EM cluster

ATLAS-CONF-2012-062

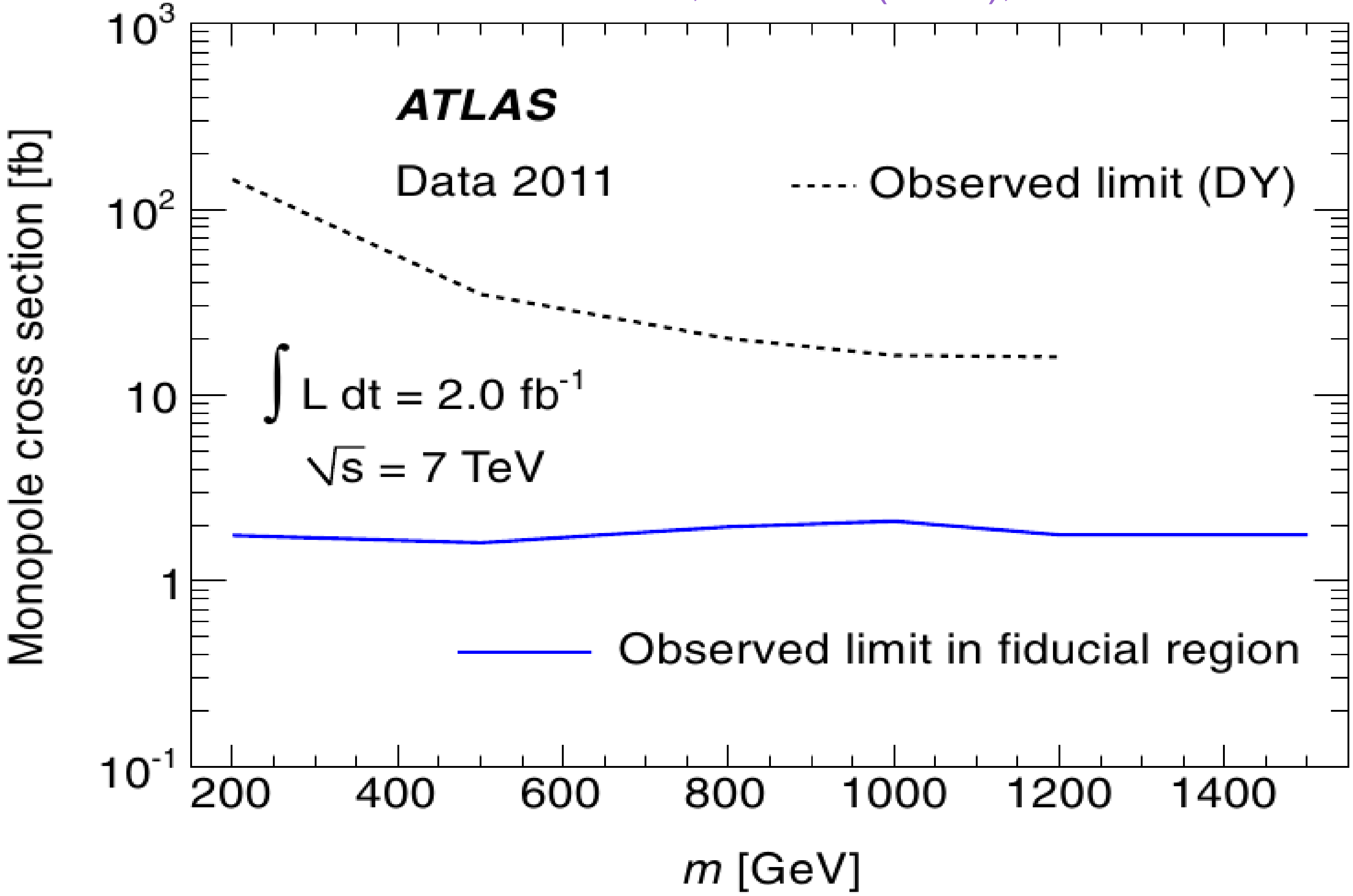


- Interpretation for magnetic monopole with minimum charge (|g| = g_D)
  - Applying HIP correction in LAr
  - Simulating monopole dE/dx and trajectory in Geant4

ATLAS monopole search – results

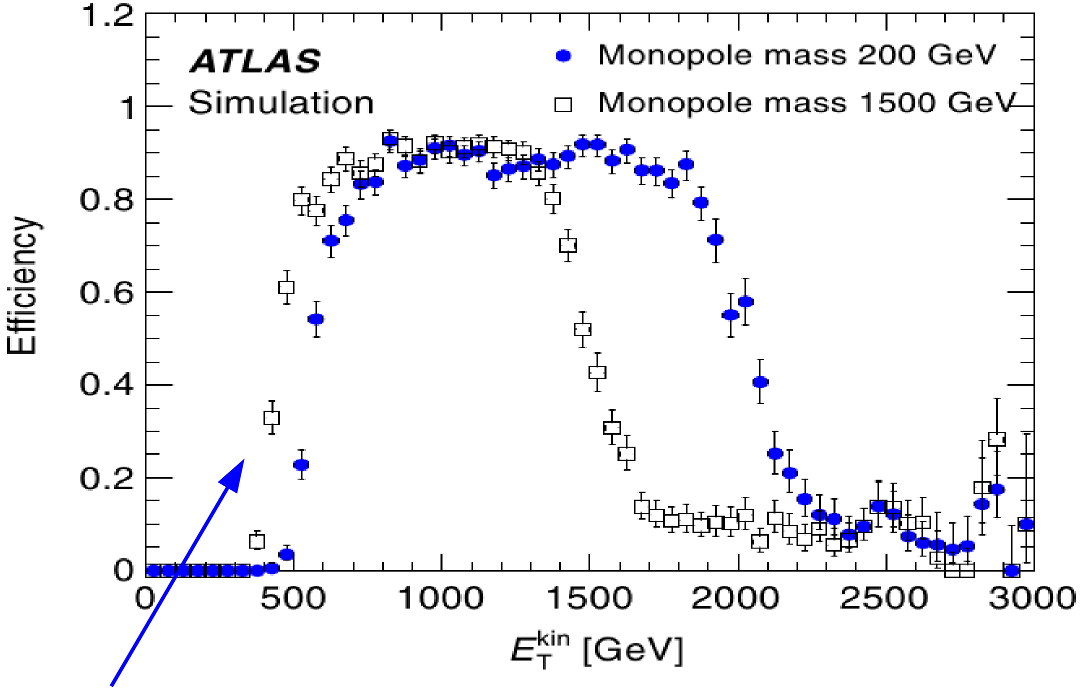
- Valid for Dirac (*N*=1) monopoles
- Blue curve is model-independent (factoring out acceptance)

PRL 109, 261803 (2012), arXiv:1207.6411



ATLAS monopole search – next step

PRL 109, 261803 (2012), arXiv:1207.6411



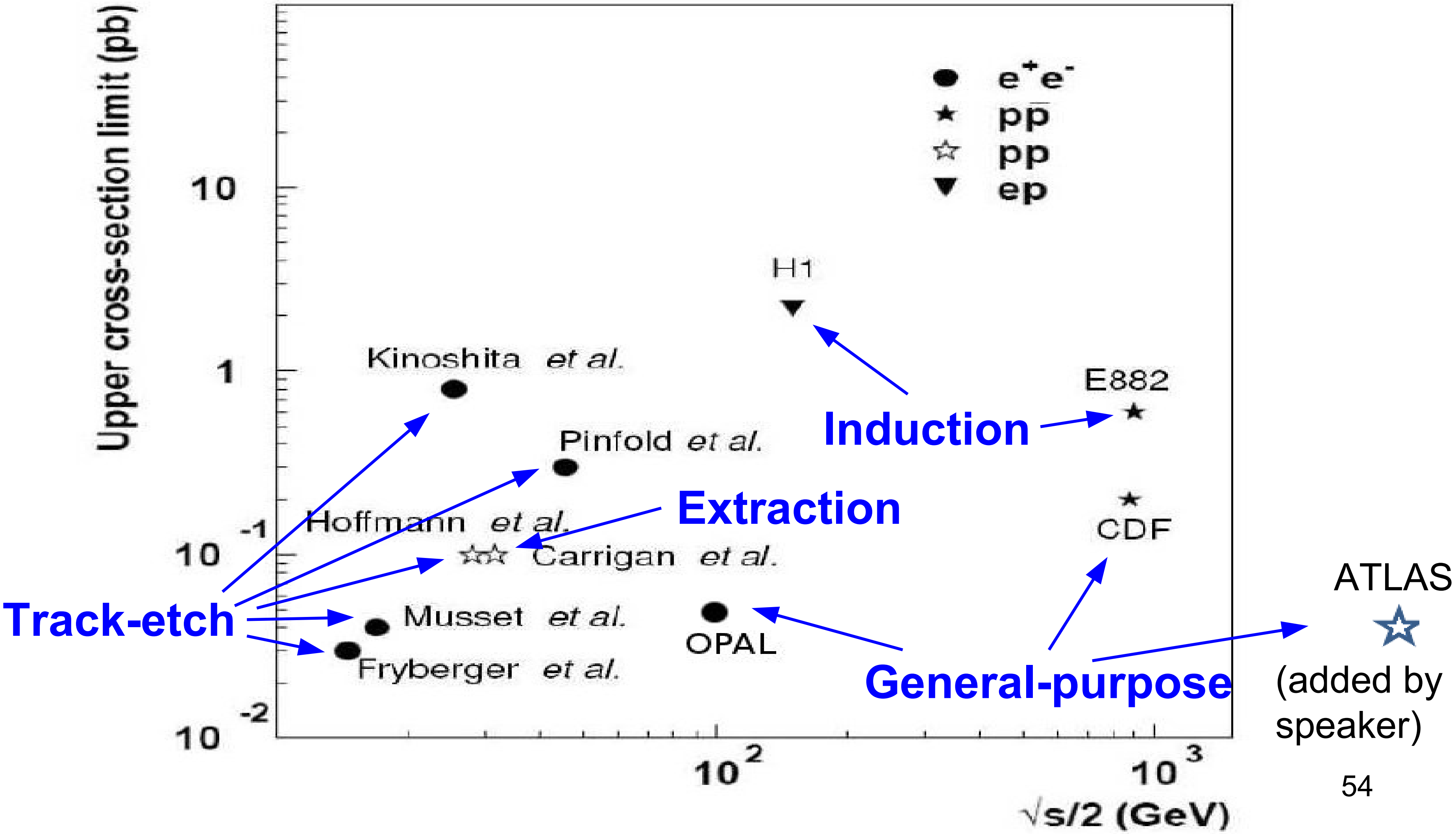
Recover monopoles stopping in first calorimeter layer

- **New dedicated high-level trigger** based on high-ionisation hits
- **Large acceptance increase, allows to probe *N* = 2**
- 7 fb^{-1} of 8 TeV data in 2012, **analysis in progress**

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

M. Fairbairn *et al.*, Phys. Rept. 438, 1 (2007), arXiv:hep-ph/0611040



Induction

Extraction

Track-etch

General-purpose

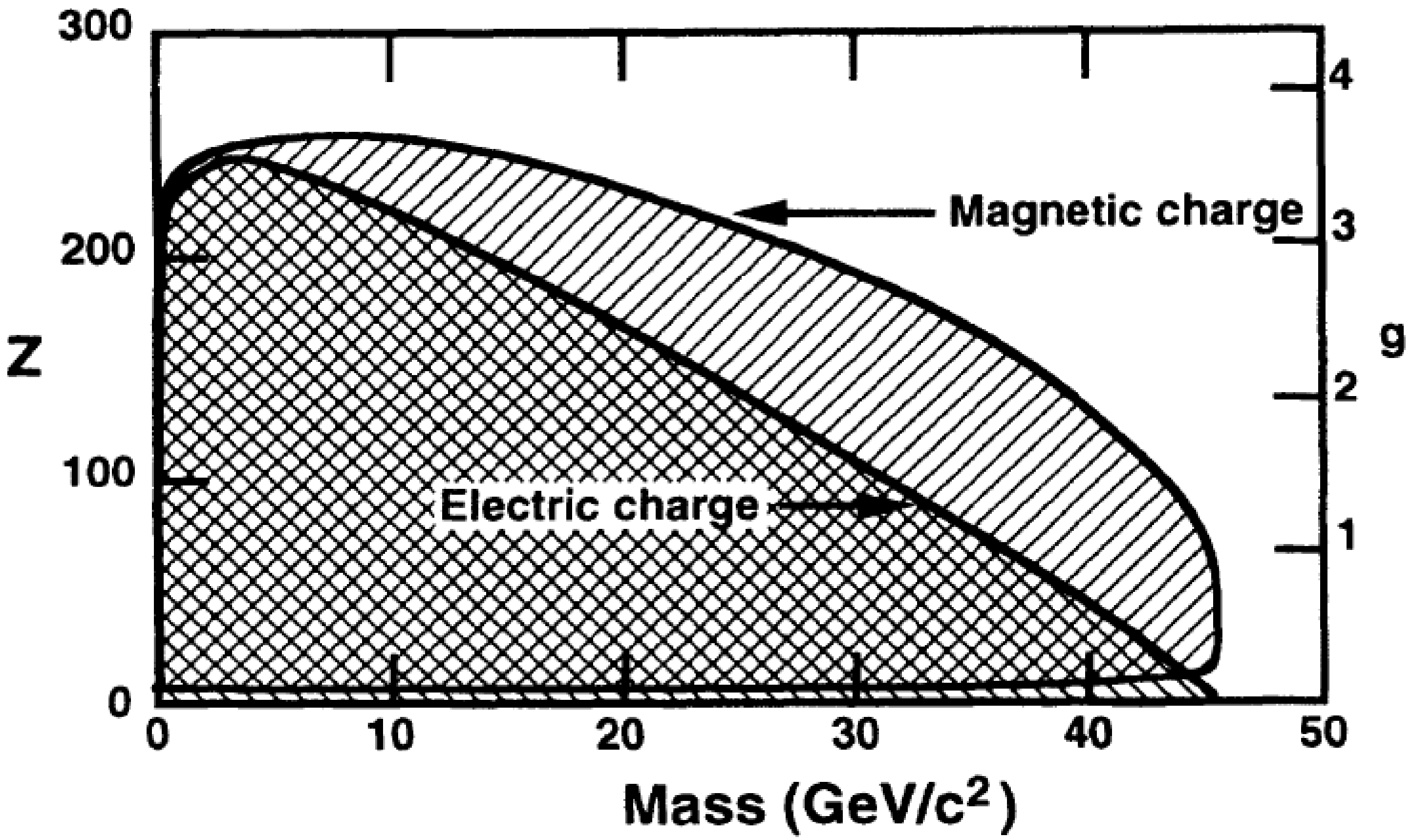
ATLAS

(added by speaker)

MODAL (LEP1, track-etch)

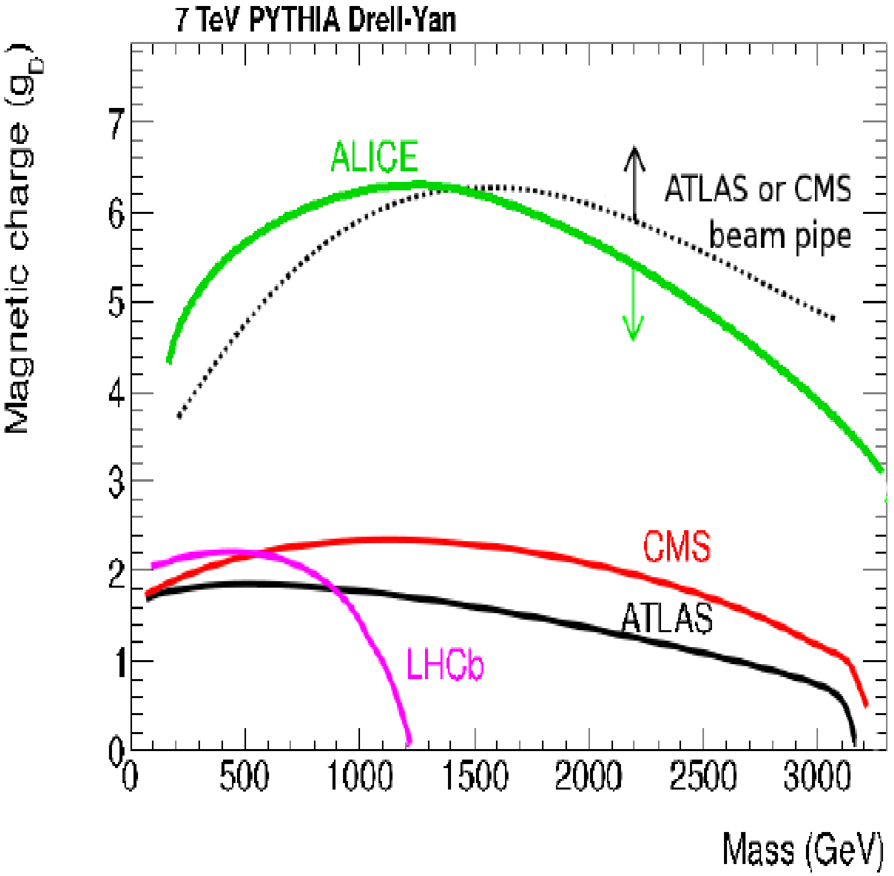
- Plastic detectors surrounding I5 interaction point
- 0.3 pb limit (up to 45 GeV HIPs)

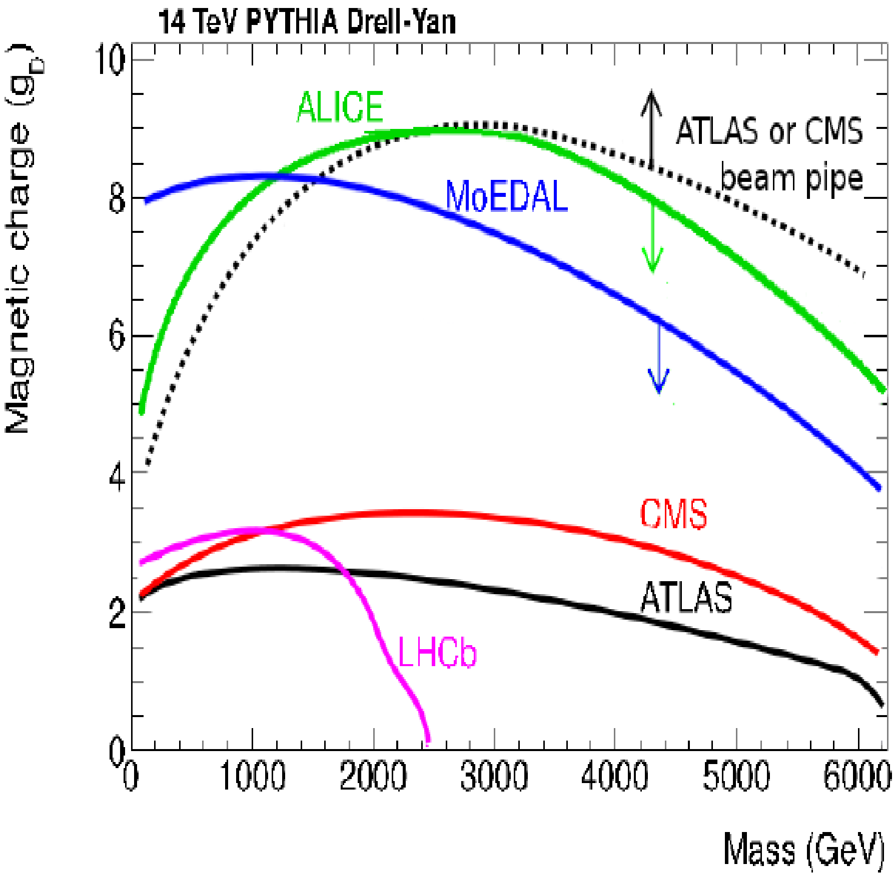
Phys. Rev. D 46, R881 (1992)



LHC reach in mass and charge

arXiv:1112.2999 (2012)



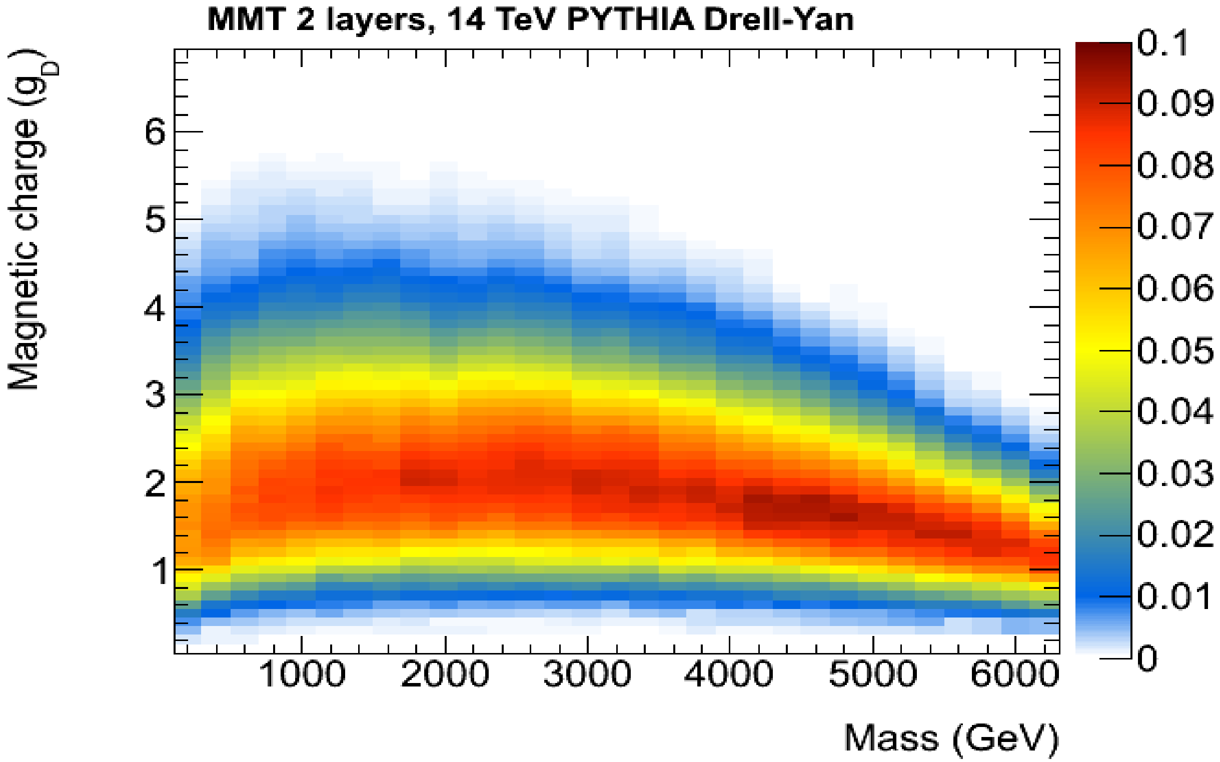


MMT design

- Material: Aluminium
  - Large nuclear dipole moment (spin 5/2) → likely to bind monopoles
  - No activation
  - Low magnetisation
  - Cheap
- Module:
  - cylinder 2.5 x 2.5 x 7 cm
  - Nicely fits magnetometer sample holder
- Two arrays
  - one in front and one on the side of VELO vacuum chamber
- MoEDAL track-etch module in front of each array

MMT acceptance estimates

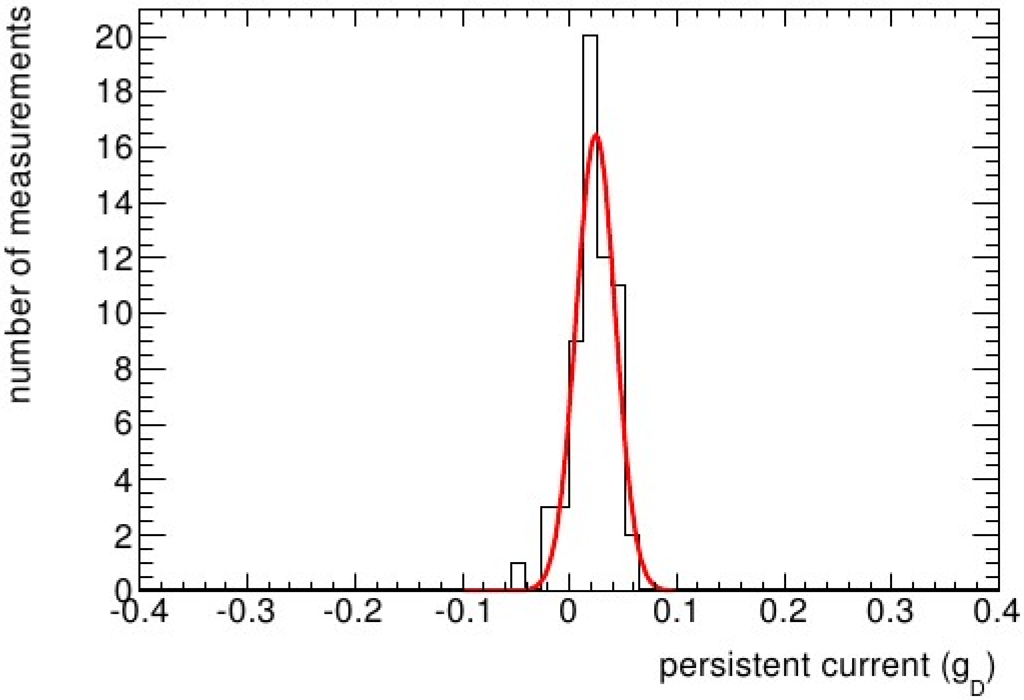
(assuming Drell-Yan pair production mechanism)



2–10 % acceptance for monopoles in the range 1–4 g_D

- Higher charge → stops in VELO chamber
- Lower charge → punches through the MMT

MMT tests with magnetometer

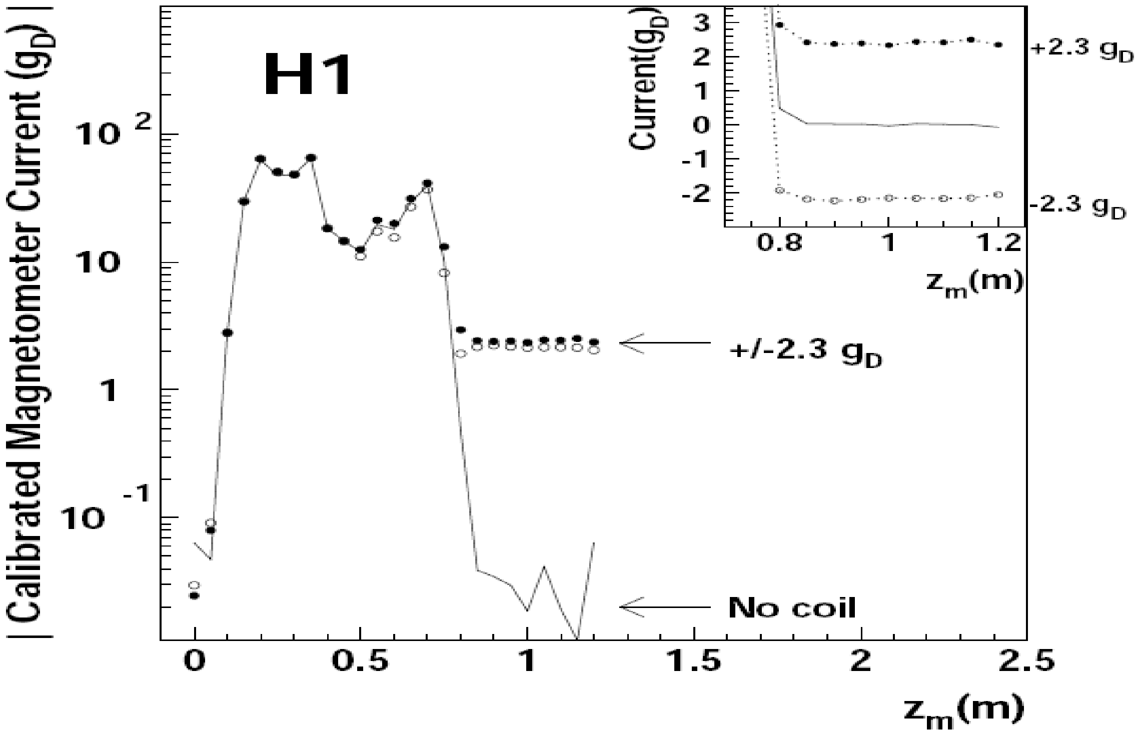


- Aluminium modules identical to those used in the MMT setup
- Monopoles with charge down to *N* = 0.5 can be identified without ambiguity

H1 beam pipe (HERA, induction)

- Monopoles and dyons with very high magnetic charges would stop in the Al beam pipe!
- 0.1 – 1 pb limit (up to 140 GeV monopole with $g \geq g_D$)

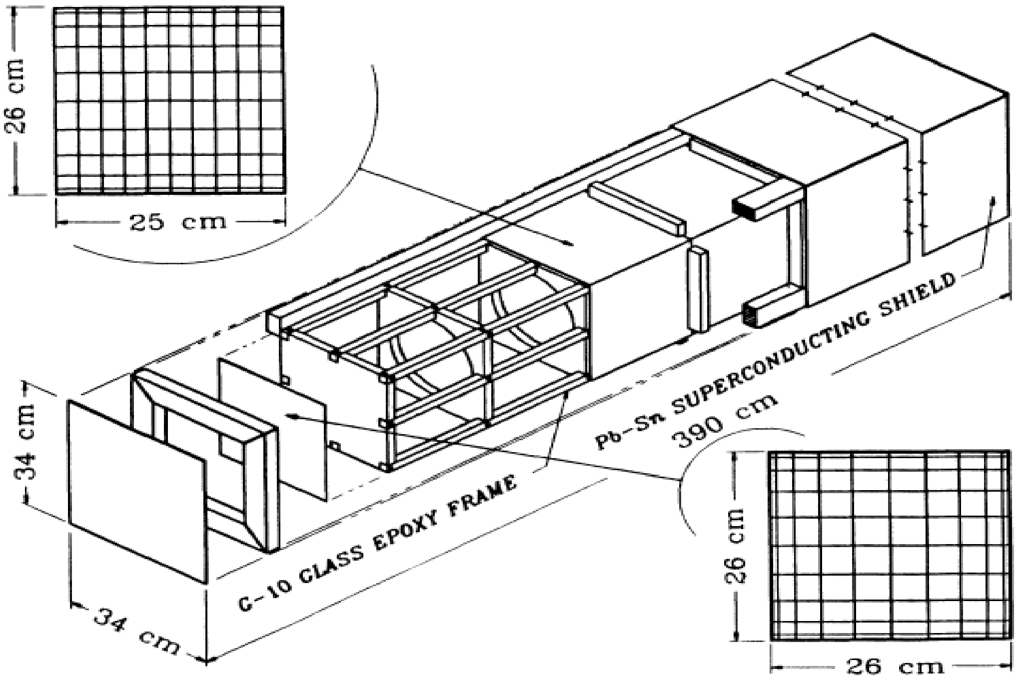
arXiv:hep-ex/0501039 (2005)



Superconducting arrays (induction)

- Response depends only on magnetic charge
  → can probe very low velocities / high masses
- Cryogenics typically limit area to 1 m^2
- Exposure time of the order of 1 year
- Spurious offsets can happen → include multiple, independent detectors (e.g. closed box)
- F < 10^{-12} $cm^{-2}s^{-1}sr^{-1}$

PRL 64, 839 (1990)
PRD 44, 622 (1991)
PRD 44, 636 (1991)

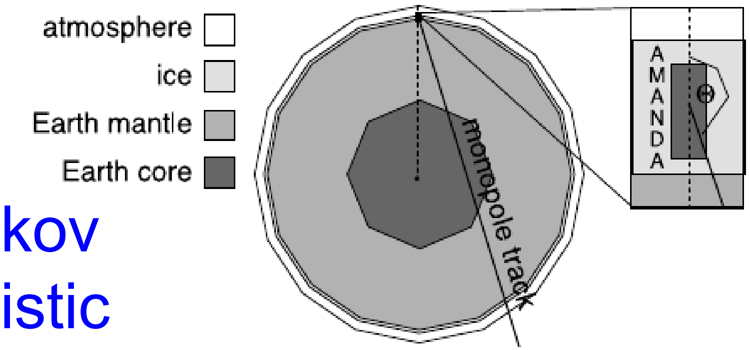


MACRO

- ~1400 m underground
- Area: 1000 m^2, 10 m height
- Exposure: 5 years
- Various detection techniques:
  - Scintillator (time-of-flight): $0.0001 < \beta < 0.01$
  - Scintillator (dE/dx): $0.001 < \beta < 0.1$
  - Streamer tubes: $0.001 < \beta < 1$
  - Track-etch: $0.001 < \beta < 1$
- $F < 10^{-16}$ $cm^{-2}s^{-1}sr^{-1}$

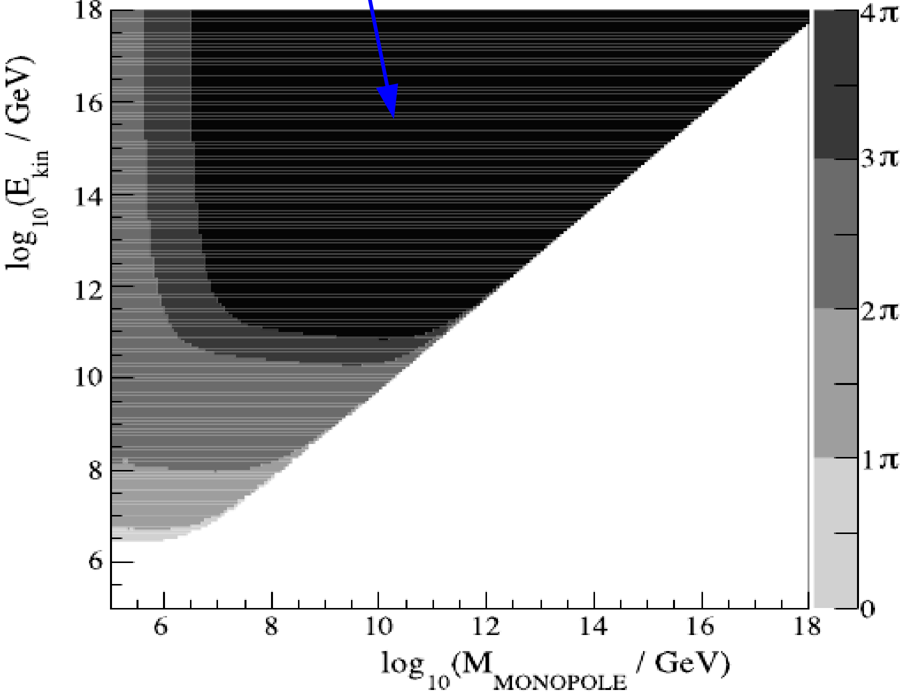
arXiv:hep-ex/0207020 (2002)

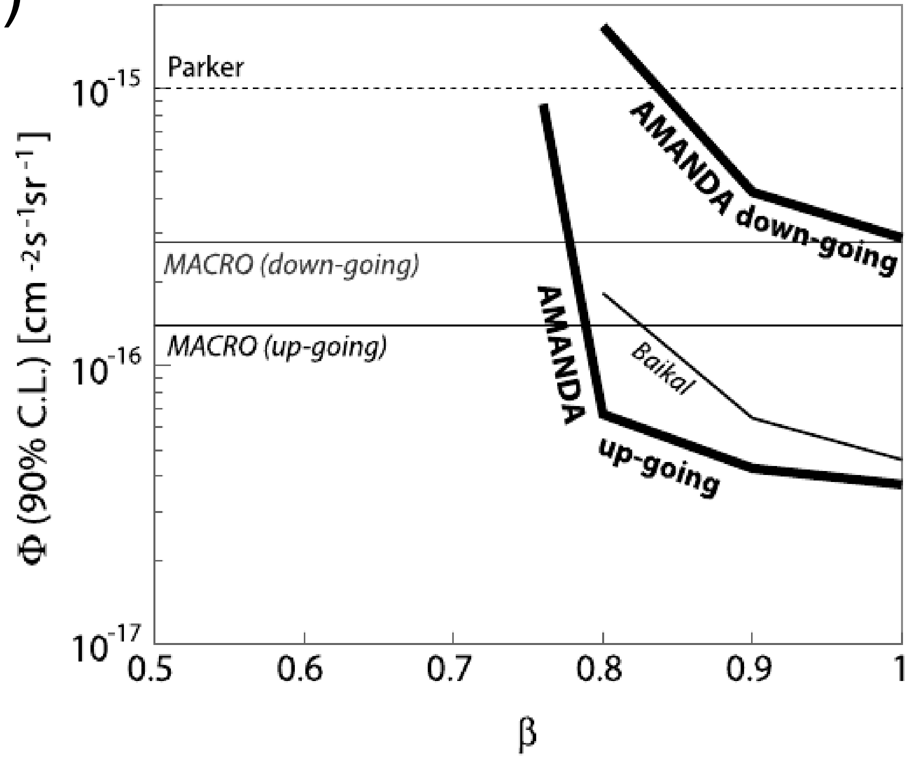
AMANDA-II (Cherenkov)



- PM arrays buried in polar ice
  - Can identify intense Cherenkov light expected from relativistic monopole ($\beta > 0.8$)
- Dark area: sensitive to up-going (much less backgrounds)

EPJC 69, 361 (2010)

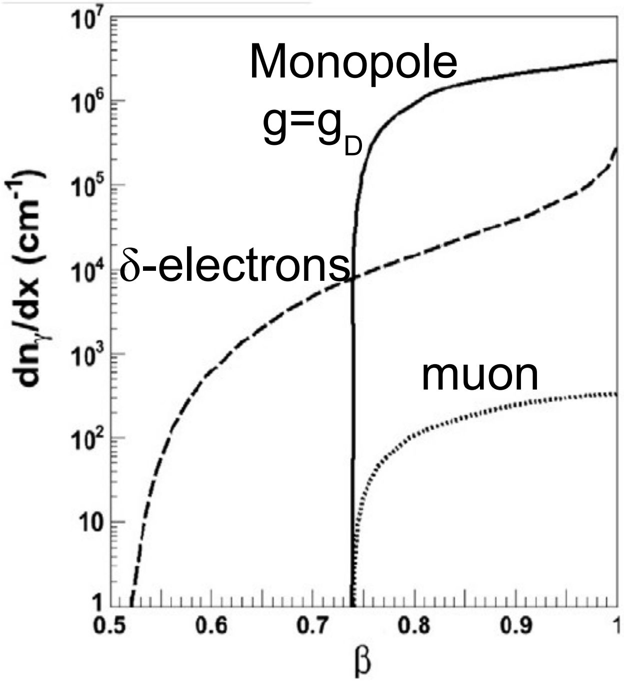




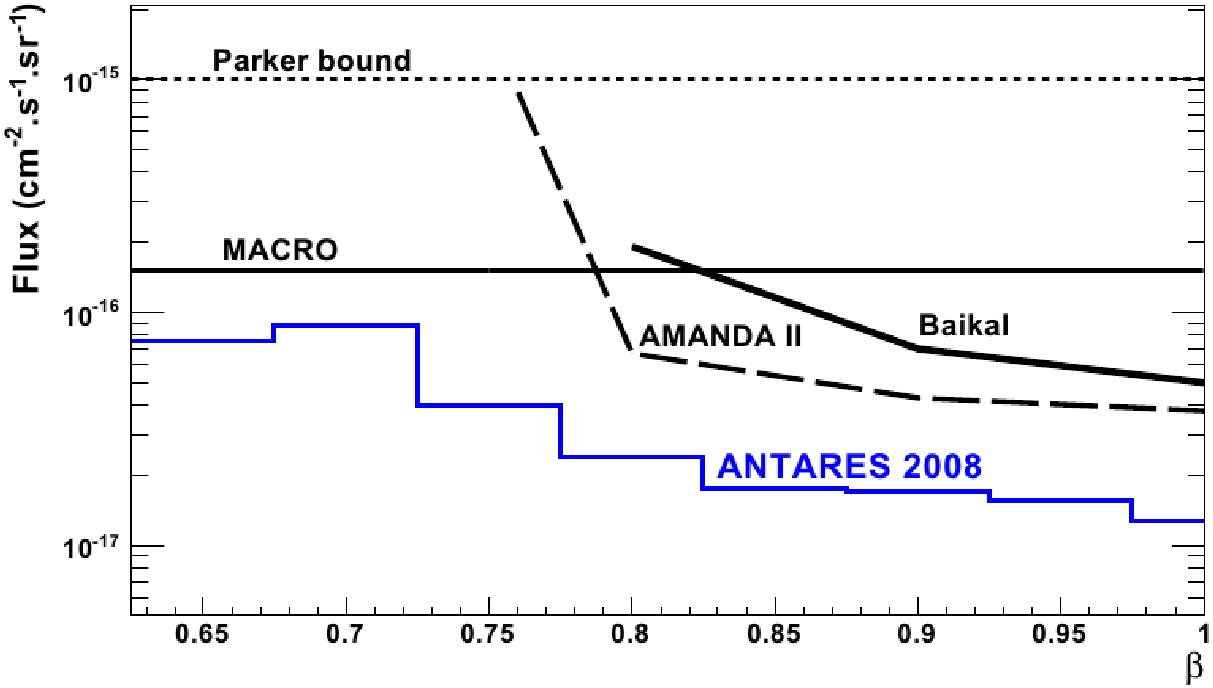
ANTARES search

- Relativistic ($\beta > 0.75$) → abundant Cherenkov light
- Only upgoing signals considered to reduce atmospheric muon backgrounds → need monopole to traverse the Earth ($m > 10^7$ GeV)

Density of photons emission



Astropart. Phys. 35, 634 (2012), arXiv:1110.2656



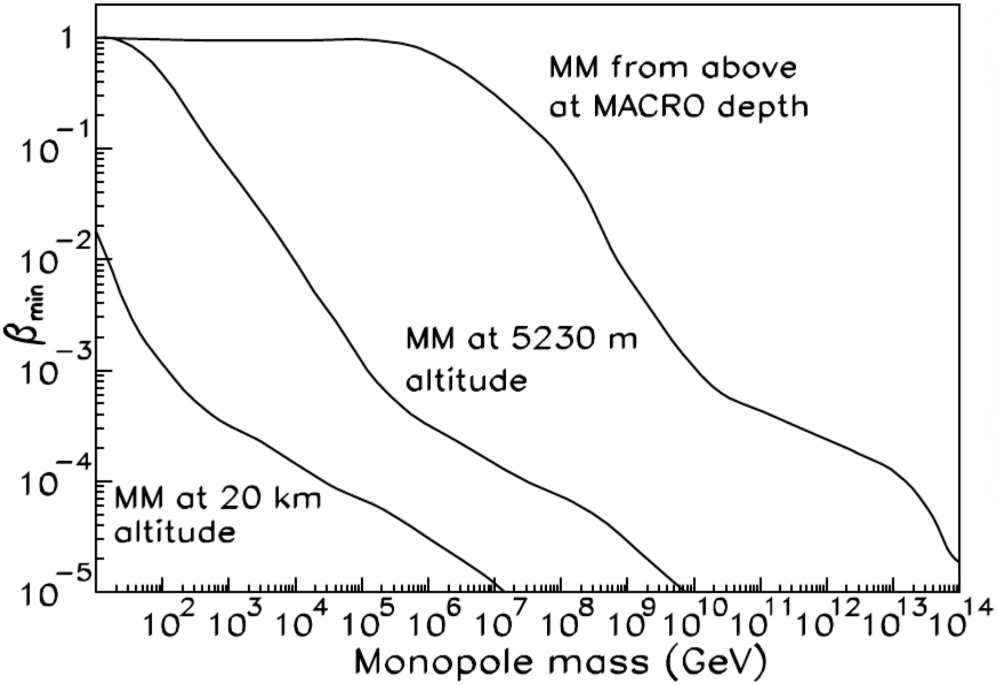
SLIM (track-etch)

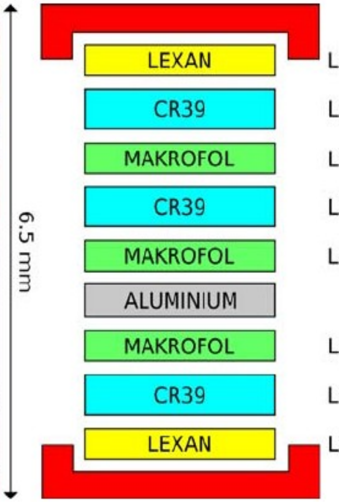
- Altitude: 5230 m

(Chacaltaya observatory)

- Area: 400 m^2
- Exposure: 4 years
- F < 10^{-15} $cm^{-2}s^{-1}sr^{-1}$

arXiv:0801.4913 (2008)

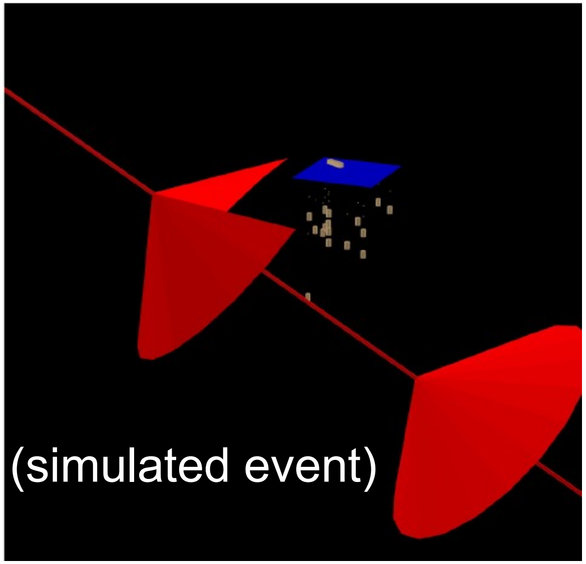




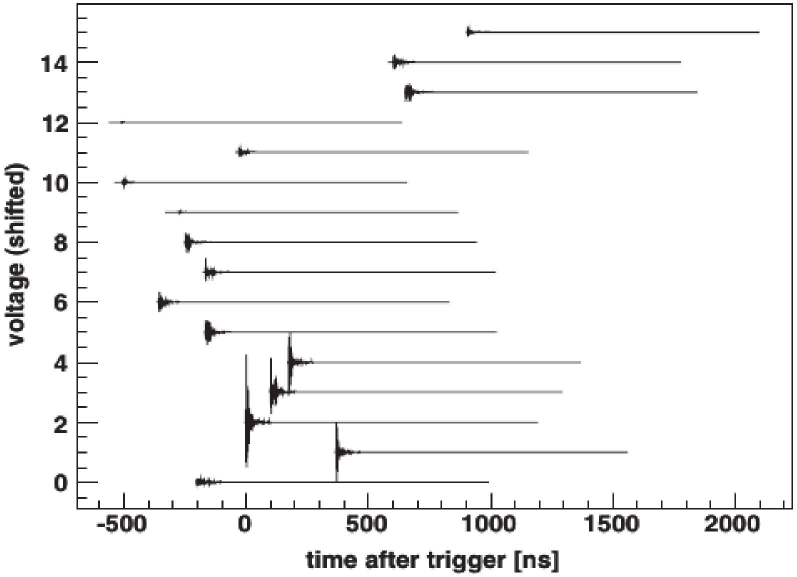
RICE (radio Cherenkov)

- Antennas buried in polar ice
  - Can identify strong radio wave signal from coherent Cherenkov radiation expected from ultra-relativistic monopole (β ≈ 1) → "intermediate mass"
- F < 10^{-18} $cm^{-2}s^{-1}sr^{-1}$ ($\gamma > 10^7$)

arXiv:0806.2129 (2008)



(simulated event)



Old (460 Ma) mica crystals

- Very highly ionising particle causes lattice defects revealed after etching
  - **Needs assumption** of a low-velocity ($\beta \sim 10^{-3}$) monopole which captured a nucleus
- $F < 10^{-18}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$

PRL 56, 1226 (1986)