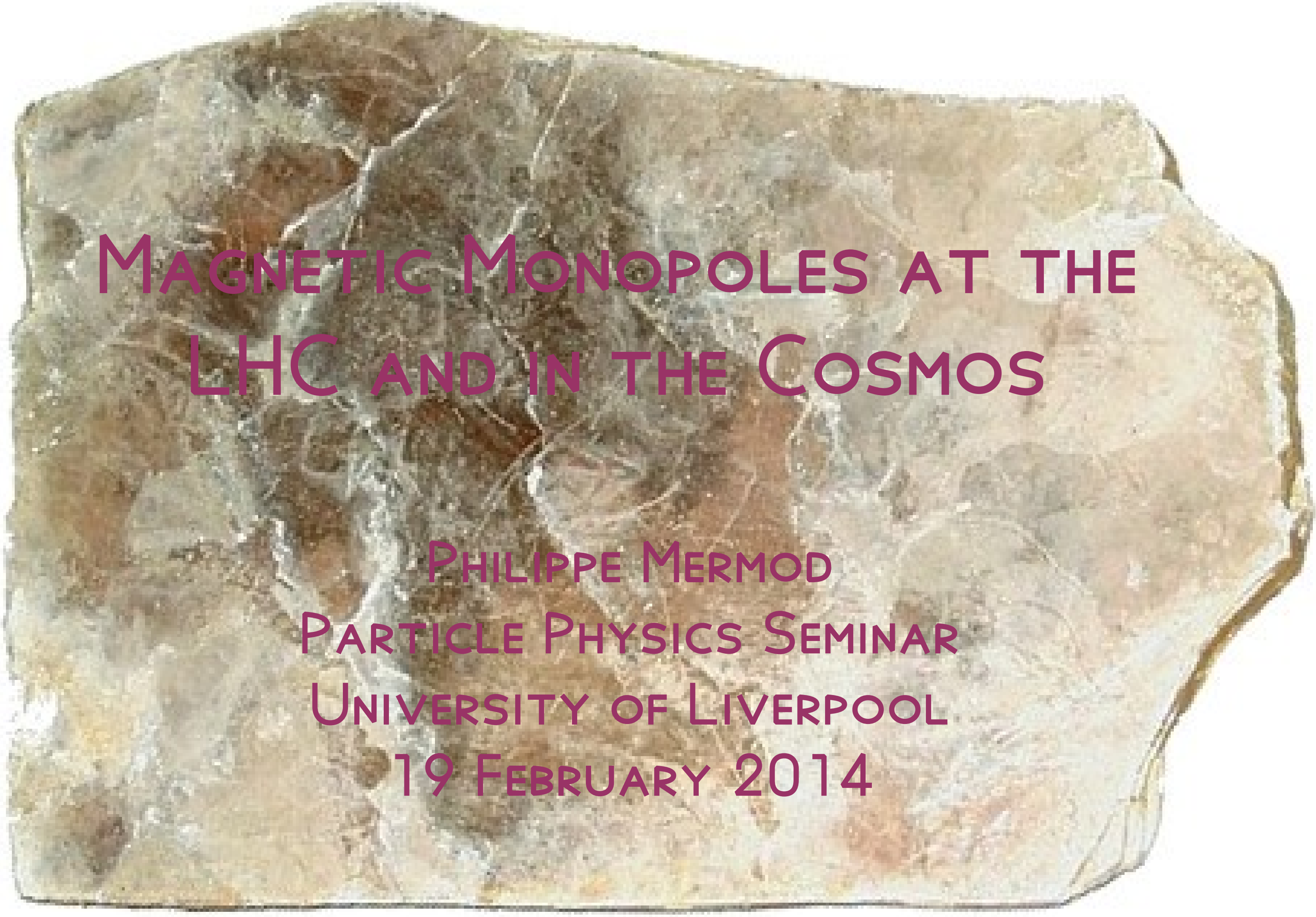
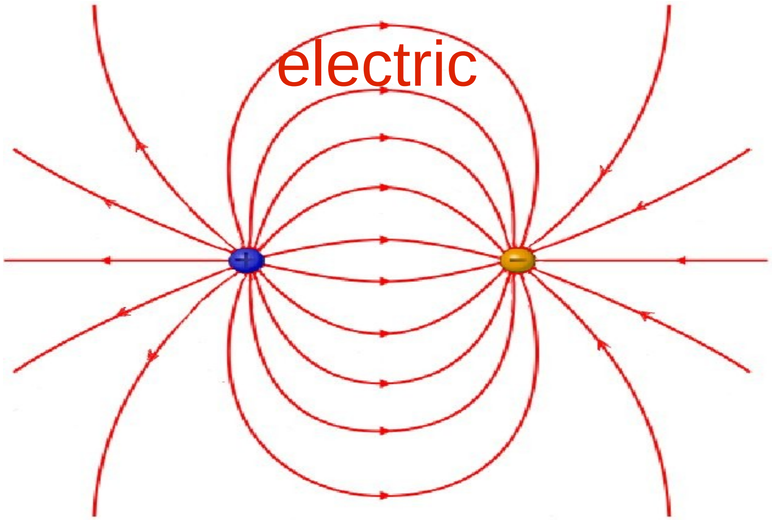
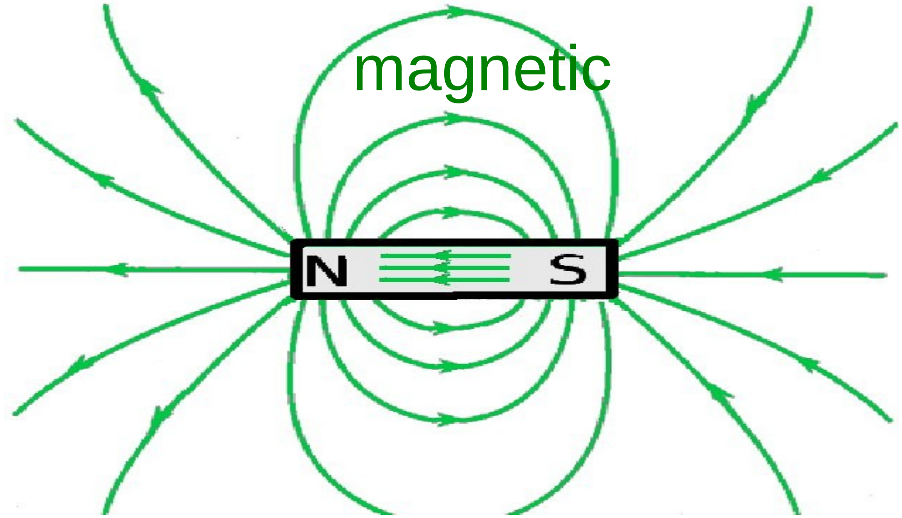


Magnetic Monopoles at the LHC and in the Cosmos

Philippe Mermod
Particle Physics Seminar
University of Liverpool
19 February 2014

MONOPOLE – THE BASICS

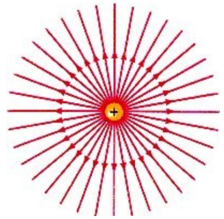




Sources of electric field exist (e.g. electrons, protons)

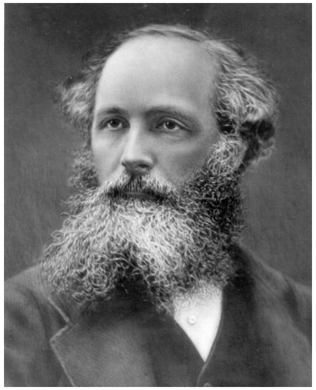
– Are there magnetic equivalents?

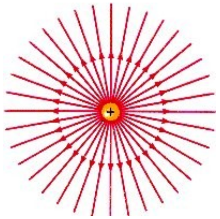
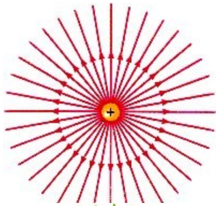
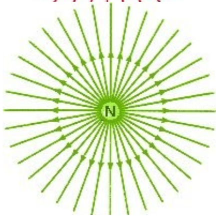
proton



magnetic monopole

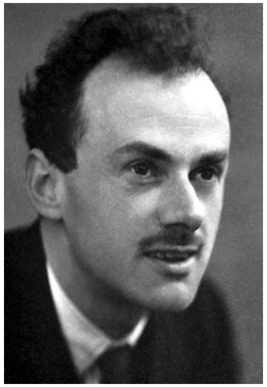
MAXWELL's EQUATIONS
(1862)

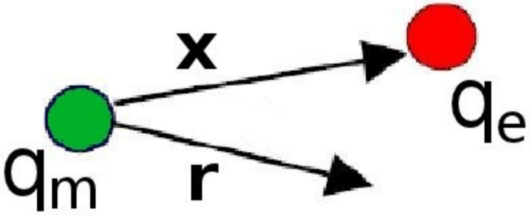


Without monopoles	With monopoles
$\nabla \cdot \mathbf{E} = 4\pi \rho_e$ 	$\nabla \cdot \mathbf{E} = 4\pi \rho_e$ 
$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B} = 4\pi \rho_m$ 
$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$	$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j_m}$
$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$	$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$

DIRAC's ARGUMENT

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





$$\mathbf{L} = \int \mathbf{r} \times \mathbf{E} \times \mathbf{B} \, d\mathbf{r} = \frac{\mu_0 q_e q_m}{4\pi} \hat{\mathbf{x}}$$
$$\Rightarrow q_e q_m = n \frac{h}{\mu_0} \ (n \text{ integer number})$$

Explains quantisation of electric charge!

– Fundamental magnetic charge (with $q_m = gec$ and $n = 1$)

$$g_D = h/(\mu_0 e^2 c) = 68.5$$

– Ionisation at high velocities $\propto g^2$
→ >4500 times more than a proton!

't HOOFT AND POLYAKOV's GUT MONOPOLES

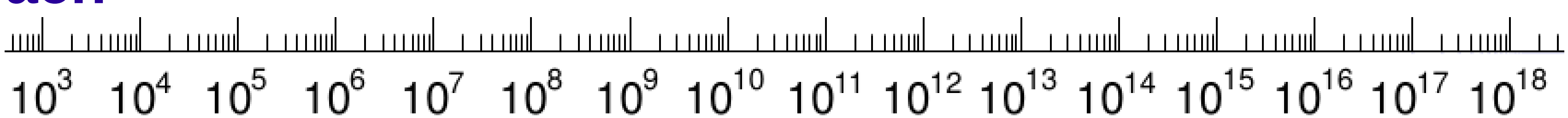
Nucl. Phys. B79, 276 (1974)

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

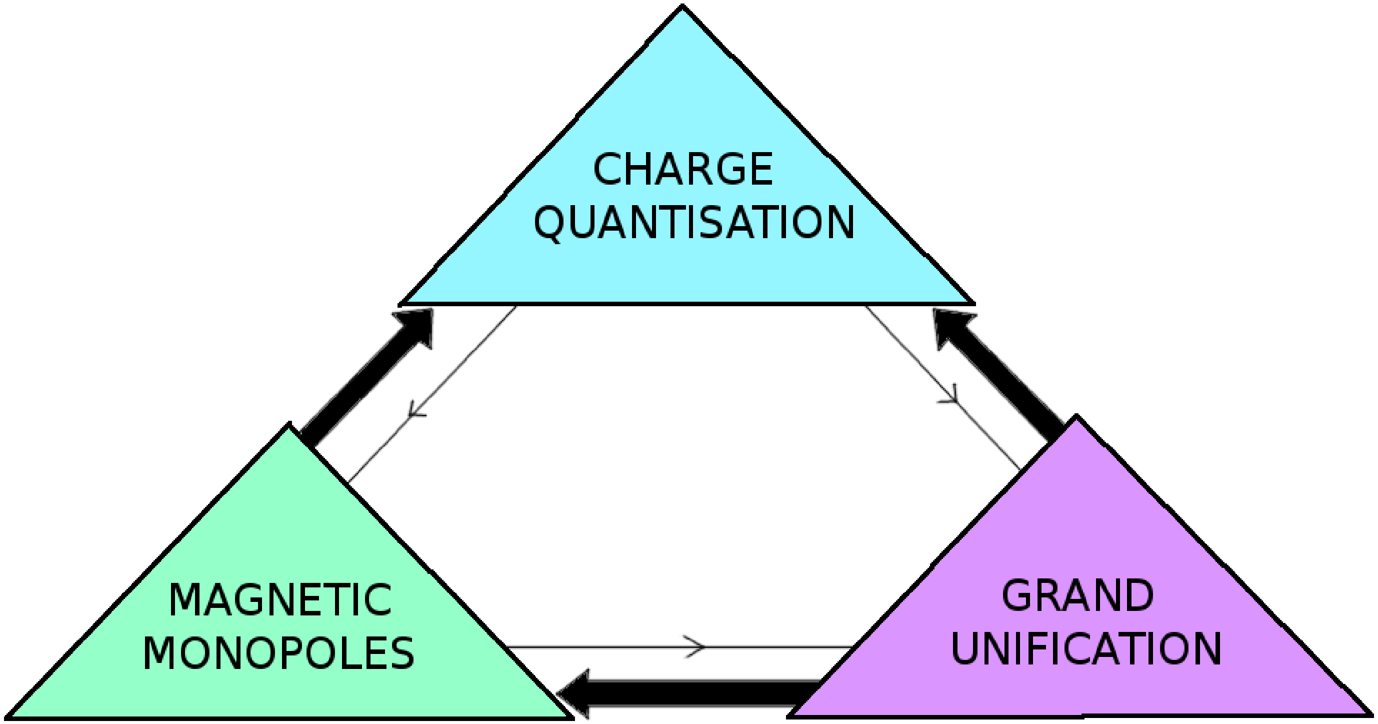
- Monopoles arise as solutions of the field equations. **Very general result!**
- Monopole mass ~ unification scale

LHC reach

GUT monopole

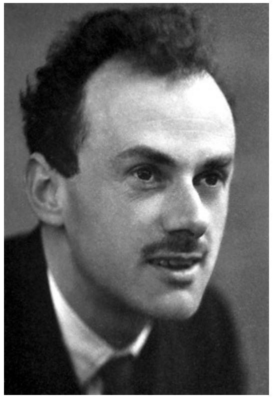


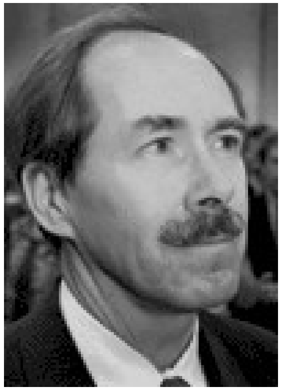
Possible monopole mass rage (GeV)



No sign of them up to mass ~1 TeV so far.

→ Explore higher masses

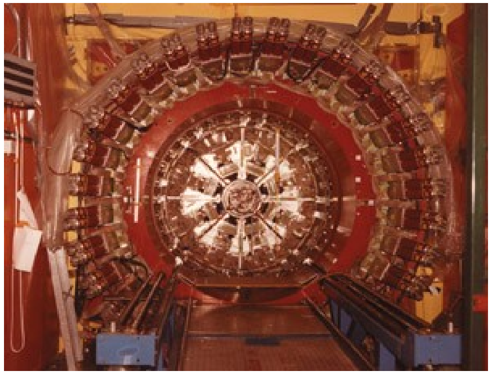




1930 1940 1950 1960 1970 1980 1990 2000 2010

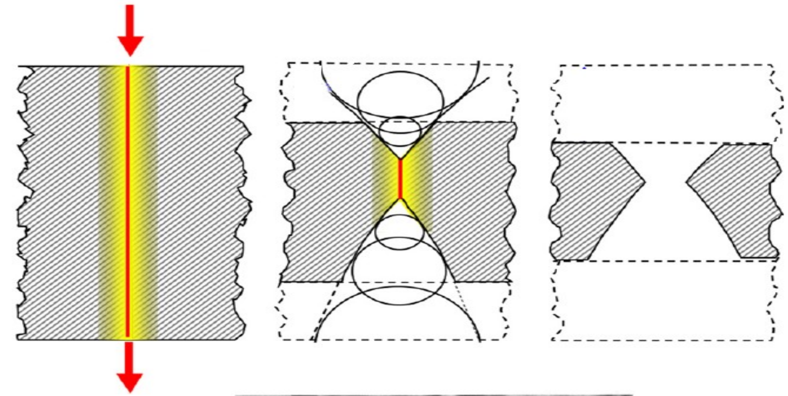
Bevatron IHEP ISR CESR SLAC LEP Tevatron

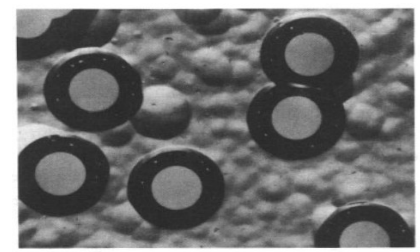
AGS Fermilab PETRA TRISTAN HERA LHC

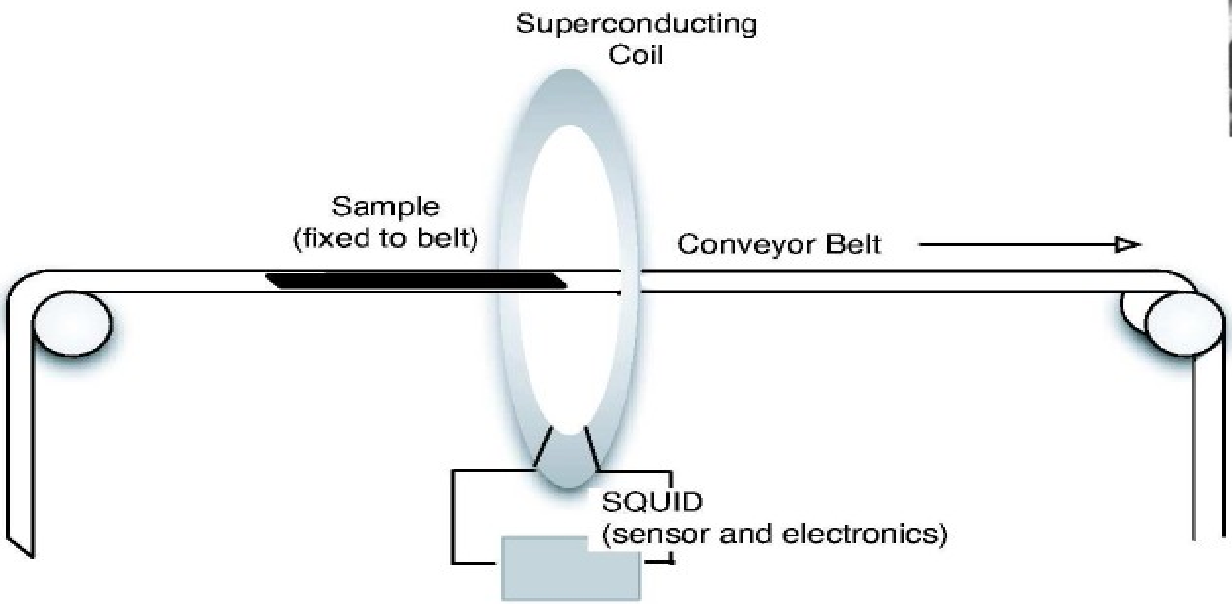


COLLIDER SEARCH TECHNIQUES FOR DIRECT DETECTION

- General-purpose detectors
- Nuclear-track detectors
- Trapping experiments – induction technique

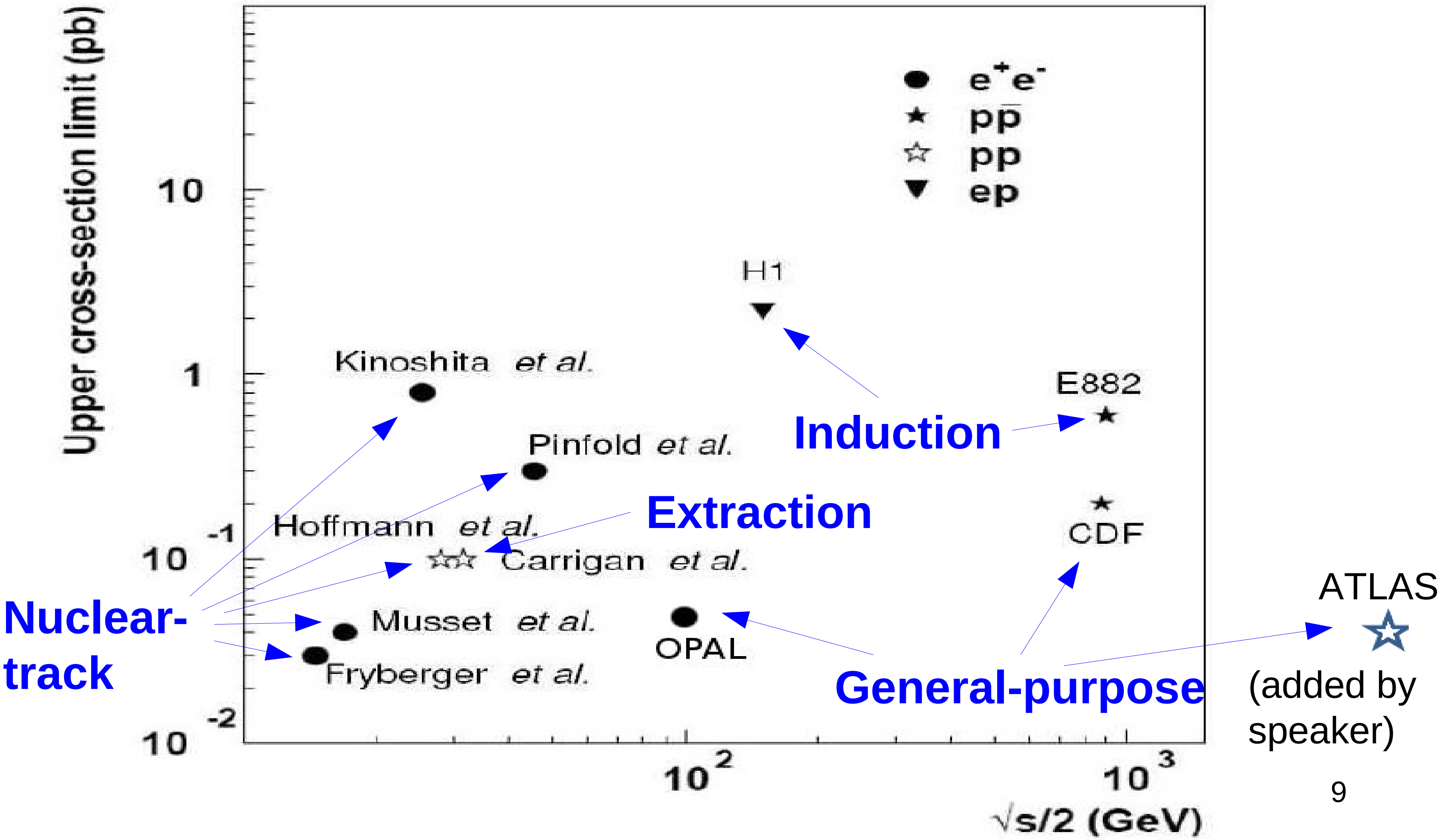






DIRECT COLLIDER SEARCHES – CURRENT LIMITS

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

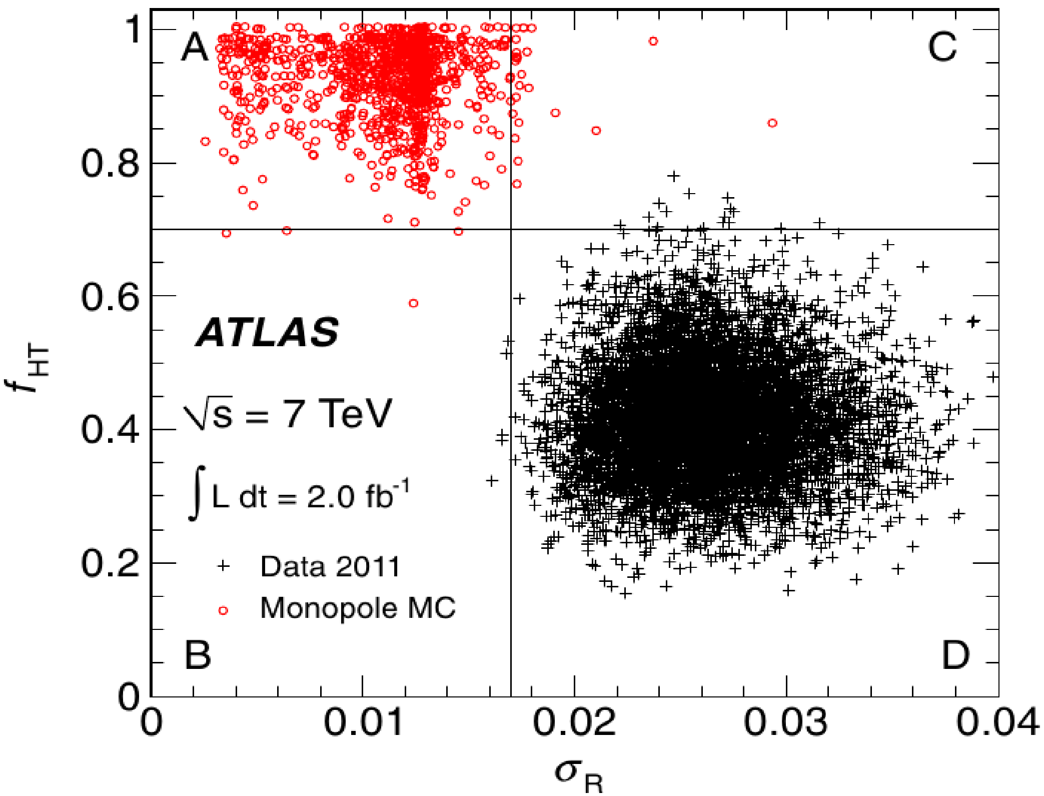


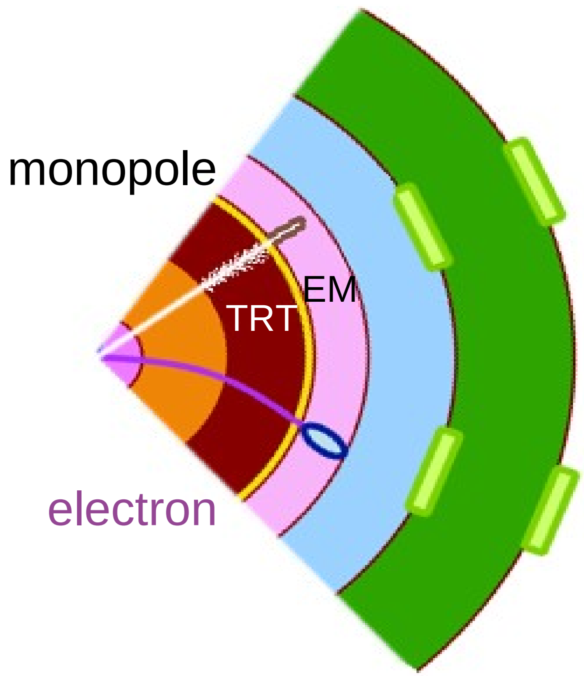
ATLAS SEARCH

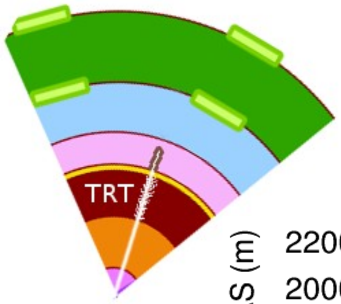
First monopole constraints at the LHC

- 2 fb^{-1} of 7 TeV *pp* collision data
- Cross section limits *for $g = g_D$* and 200 < M < 1500 GeV

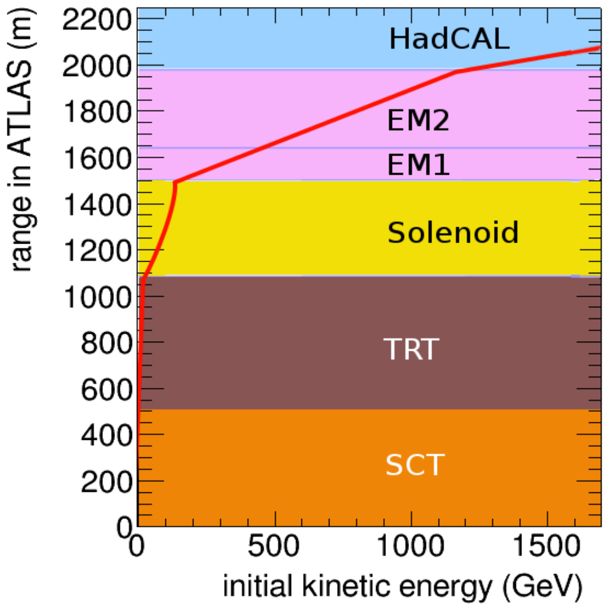
PRL 109, 261803 (2012), arXiv:1207.6411

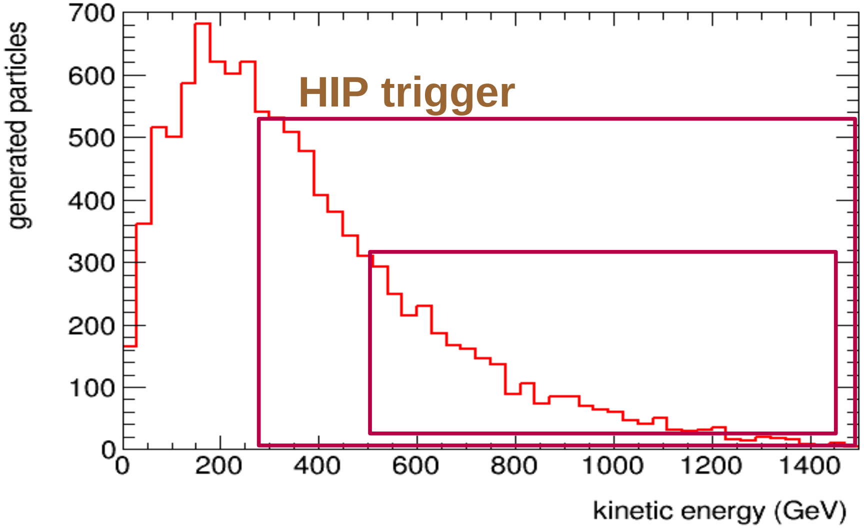


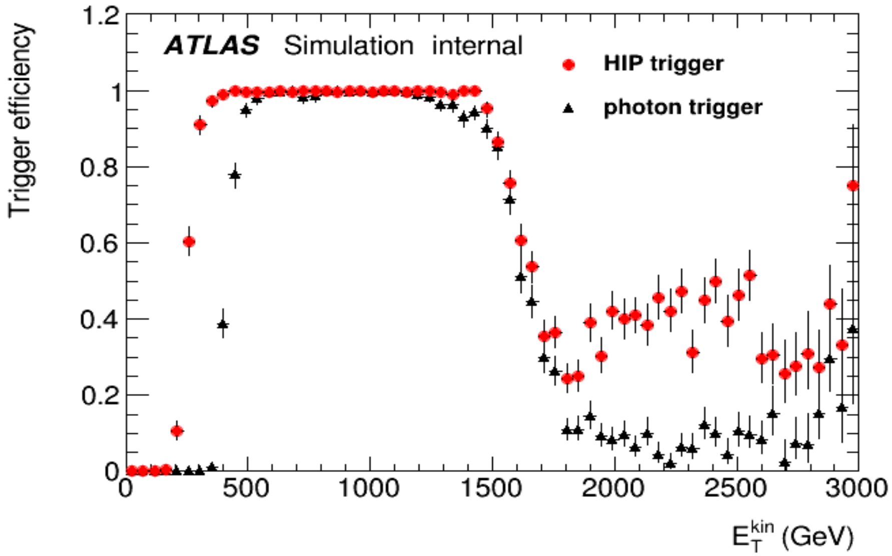




NEW ATLAS HIP SEARCHES



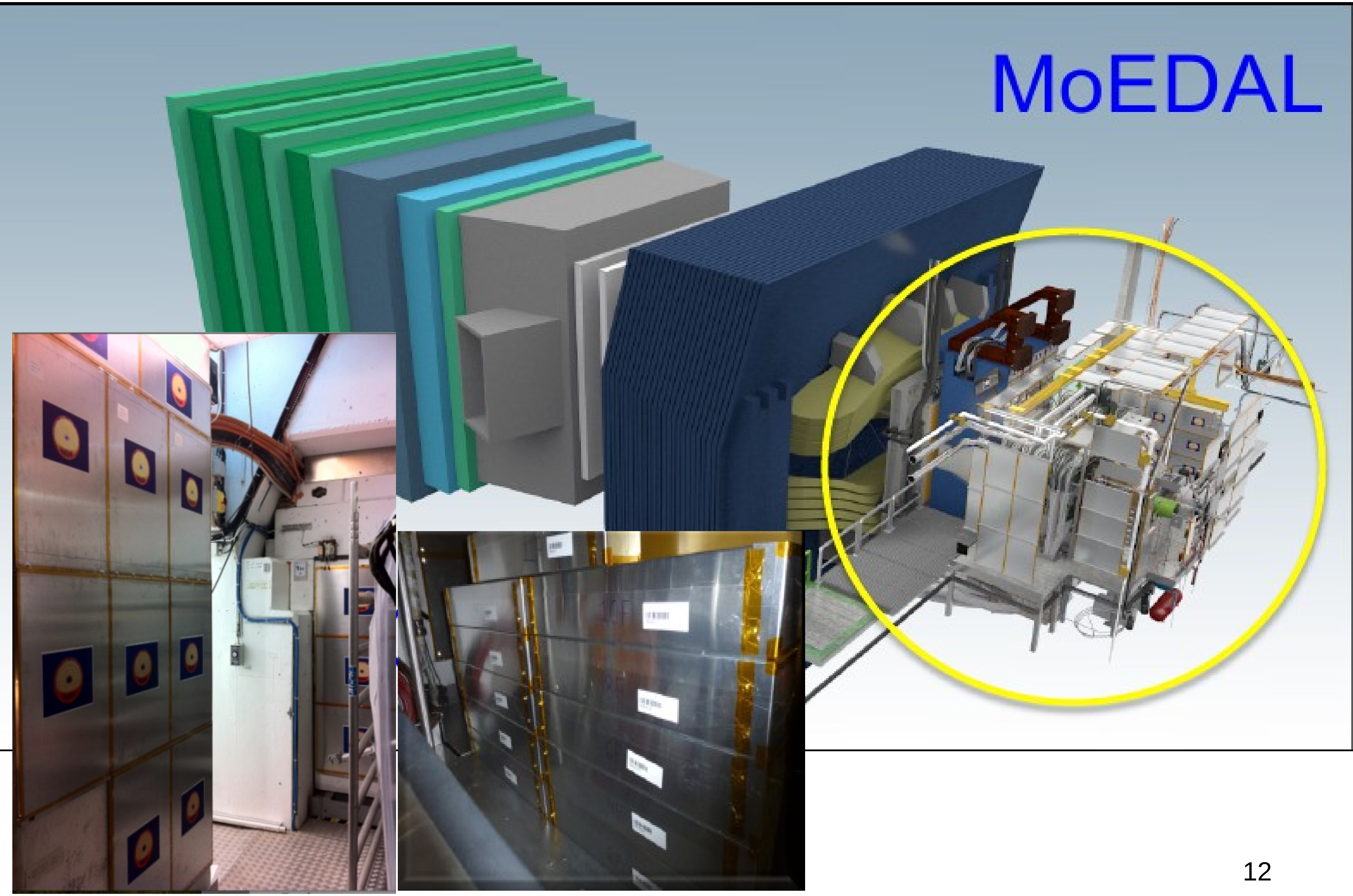




HIP trigger

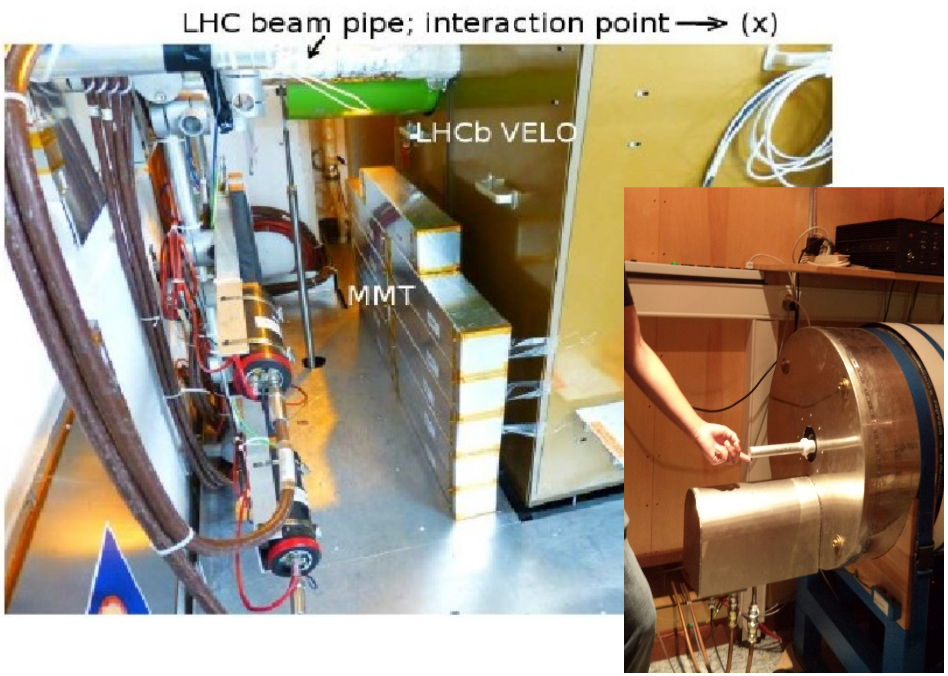
- 7 fb^{-1} of 8 TeV data
- Preparations for 14 TeV collisions

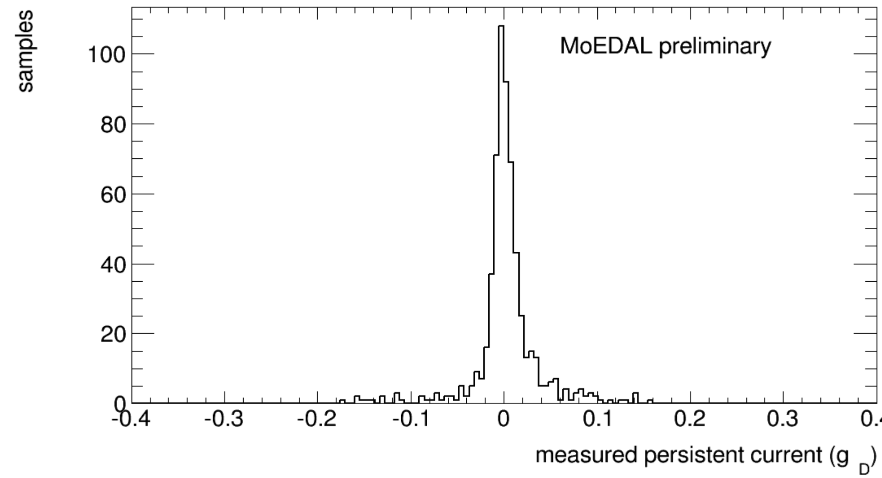
http://moedal.web.cern.ch/

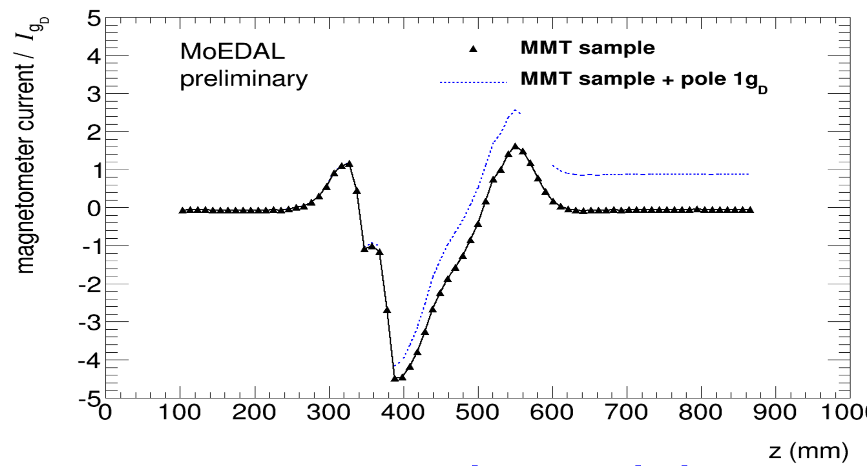


MAGNETIC MONOPOLE TRAPPER (MMT)

arXiv:1311.6940







Aluminium test array

- Exposed to 8 TeV collisions
- Scanned with superconducting magnetometer in Zürich

First LHC constraints on multiply-charged monopoles

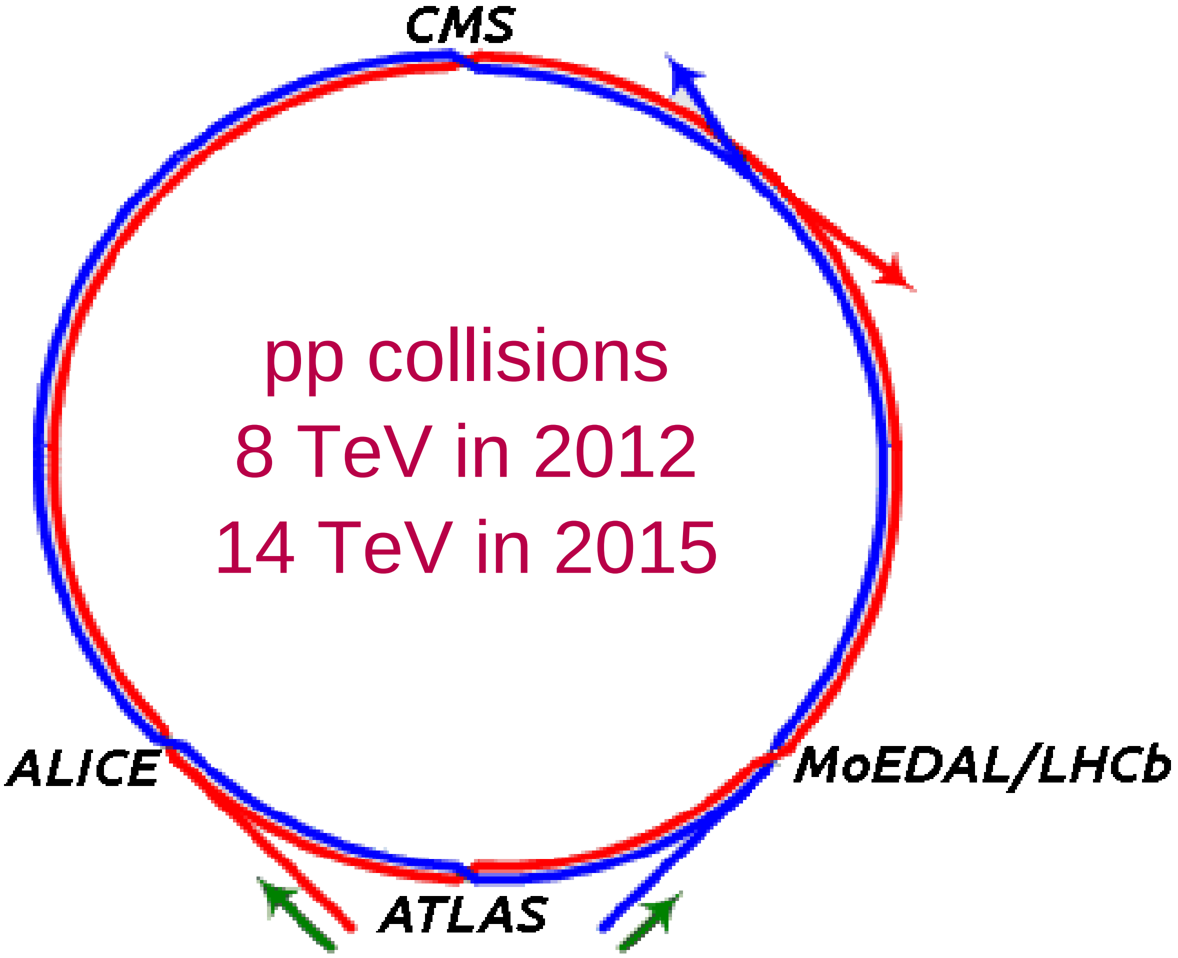
LHC BEAM PIPES

ATLAS and CMS beryllium pipes replaced after 8 TeV runs

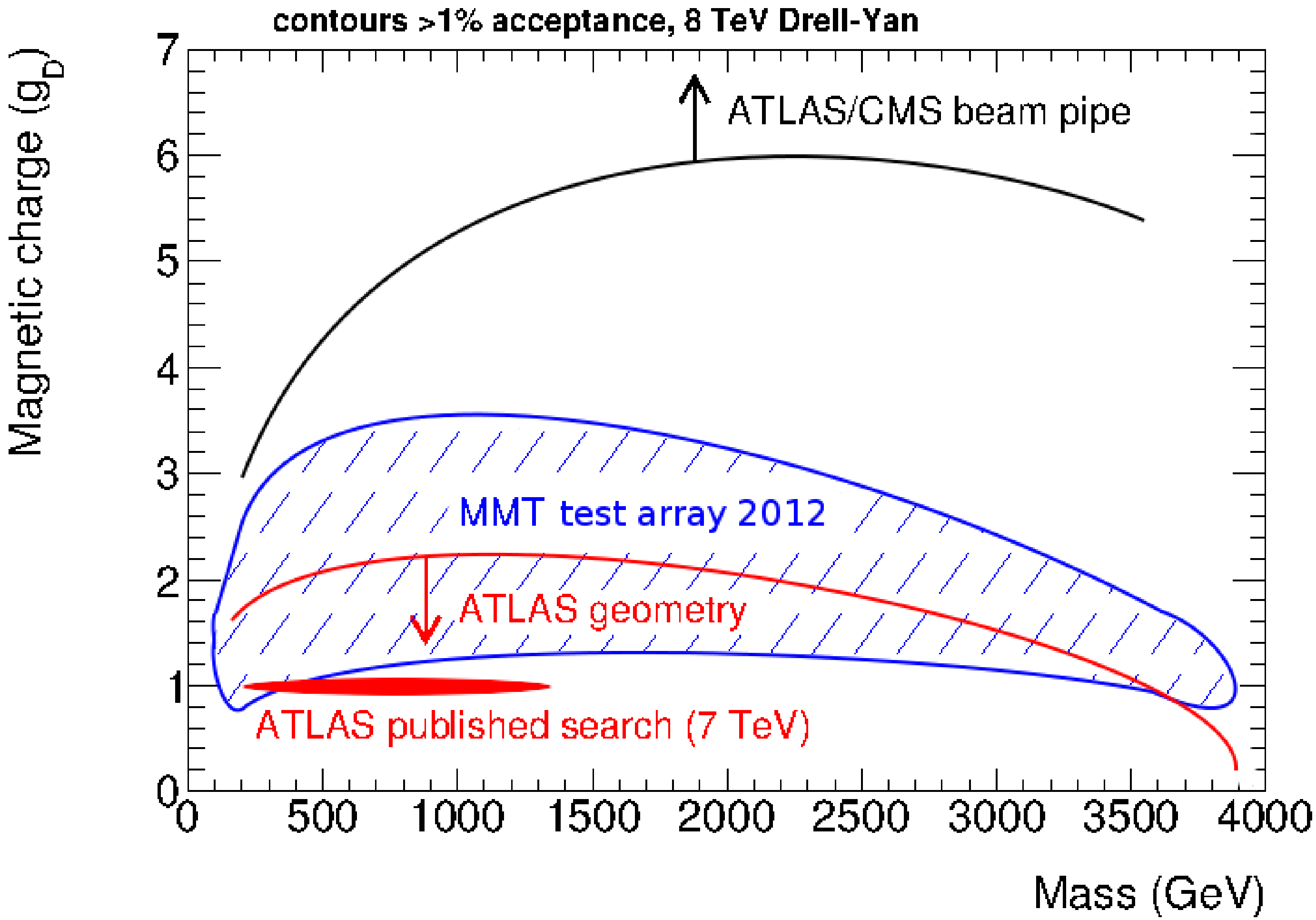
- Available for analysis in 2017
- Cut and scan with magnetometer

Only way to detect very-high-charge monopoles

EPJC 72, 1985 (2012), arXiv:1112.2999


CMS
ALICE
MoEDAL/LHCb
ATLAS
pp collisions
8 TeV in 2012
14 TeV in 2015

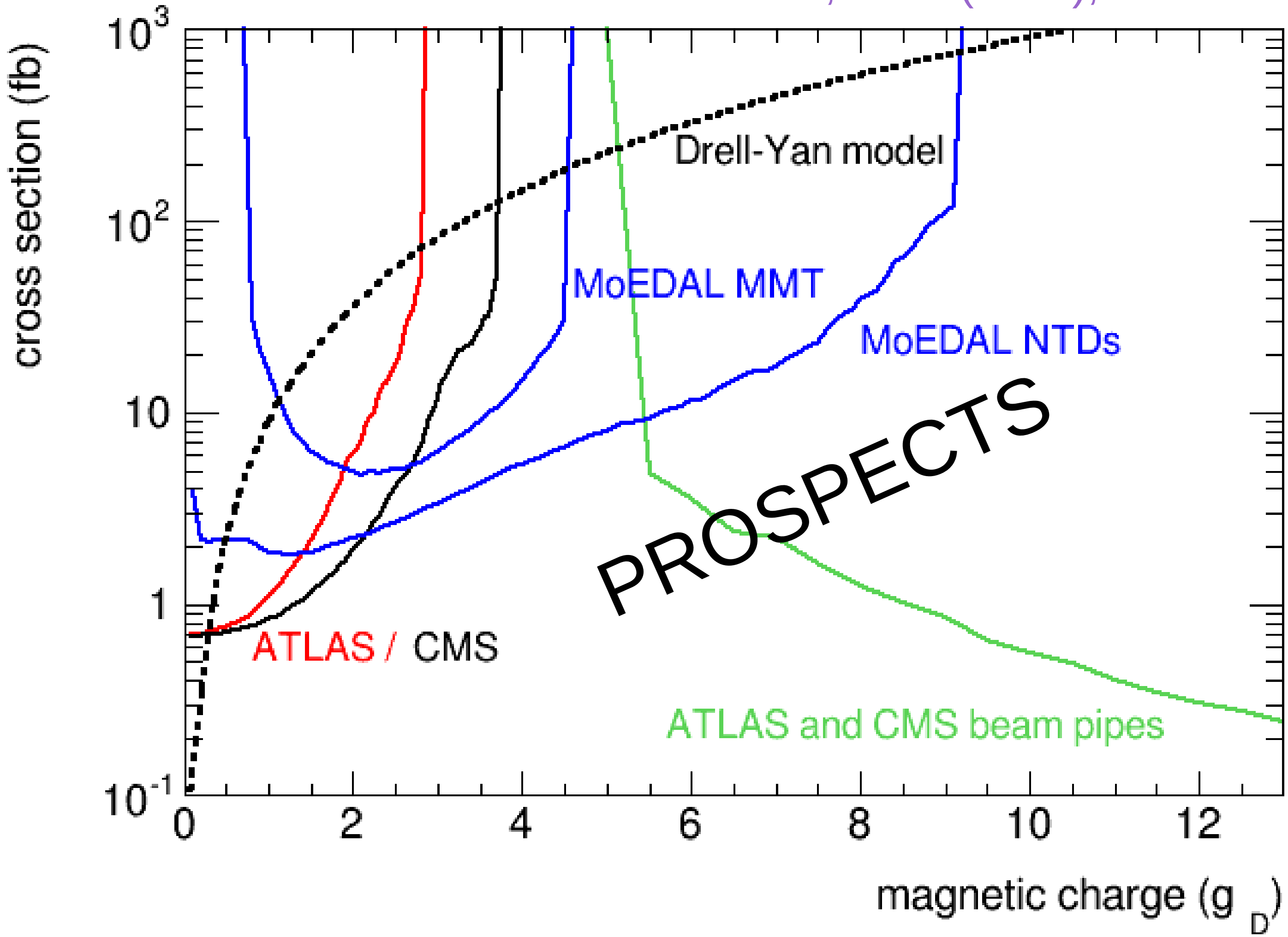
LHC 8 TeV COVERAGE



LHC 14 TeV PROSPECTS

(M = 1600 GeV)

EPJC 72, 1985 (2012), arXiv:1112.2999

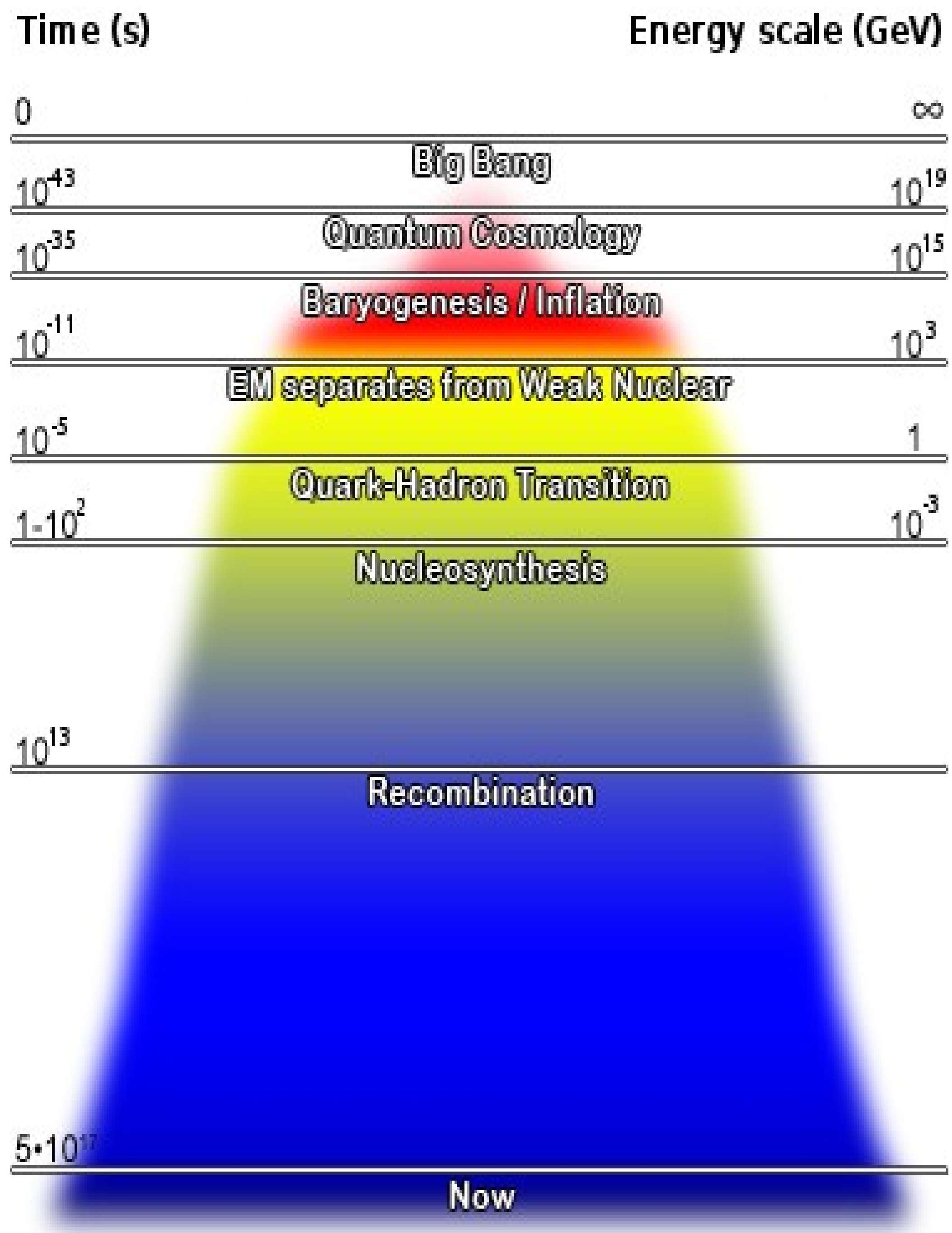


PRIMORDIAL MONOPOLES

Big Catastrophe: Enormous GUT monopole density!

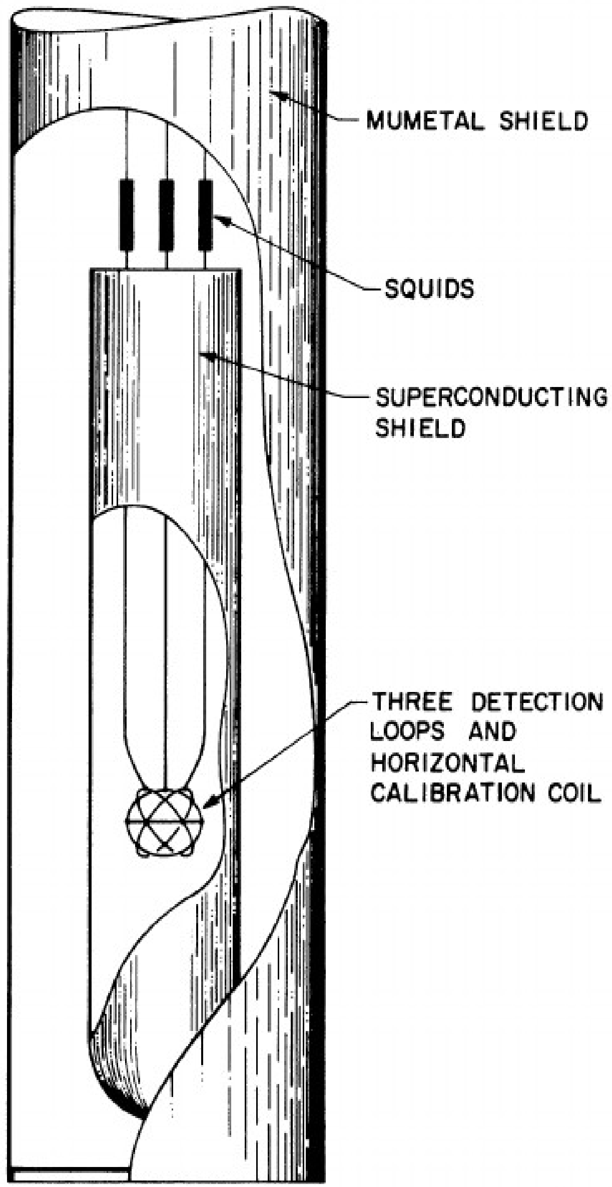
Inflation theory solves this problem by diluting the monopoles

Large uncertainty on relic monopole abundances



INDUCTION ARRAYS

- Response depends only on magnetic charge → can probe very low velocities / high masses
- Exposure ~ 1 year
- Cryogenics limit area to ~1 m^2
- Spurious offsets can happen → need multiple loops
- $F < 2 \cdot 10^{-13}$ $cm^{-2}s^{-1}sr^{-1}$



PRL 64, 835 (1990)
PRL 64, 839 (1990)
PRD 44, 622 (1991)
PRD 44, 636 (1991)

IONISATION ARRAYS – MACRO

- ~1400 m underground
- 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: $0.001 < \beta < 1$
  - Nuclear-track: $0.001 < \beta < 1$
- $F < 10^{-16}$ cm^{-2}s^{-1}sr^{-1}

EPJC 25, 511 (2002), arXiv:hep-ex/0207020

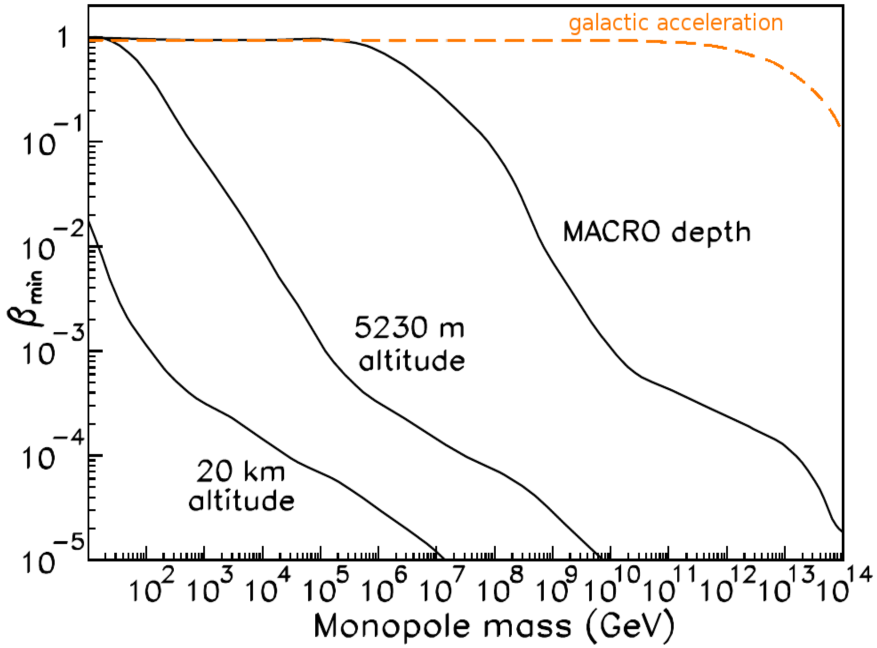
SLIM

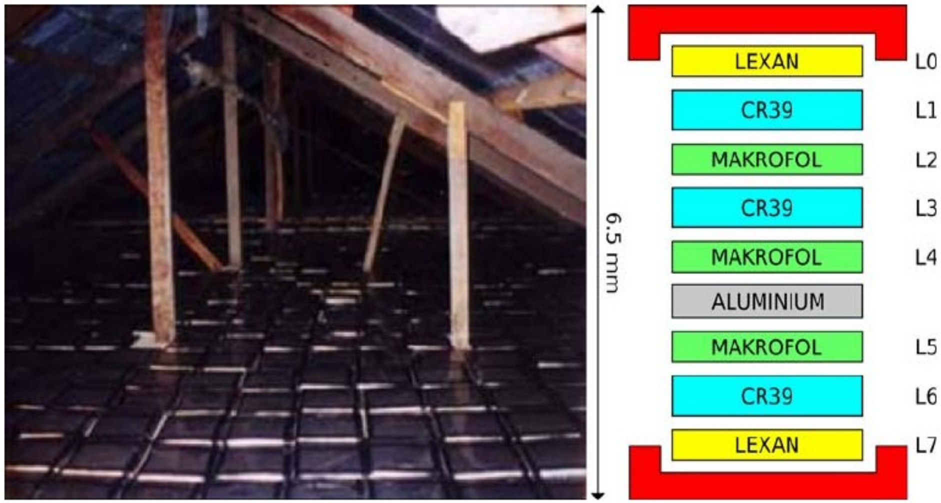
- Altitude: 5230 m

(Chacaltaya observatory)

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

EPJC 55, 57 (2008), arXiv:0801.4913

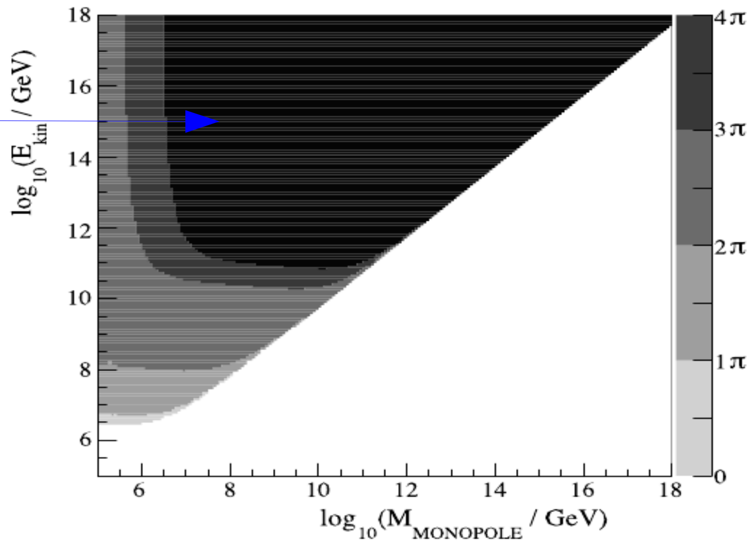




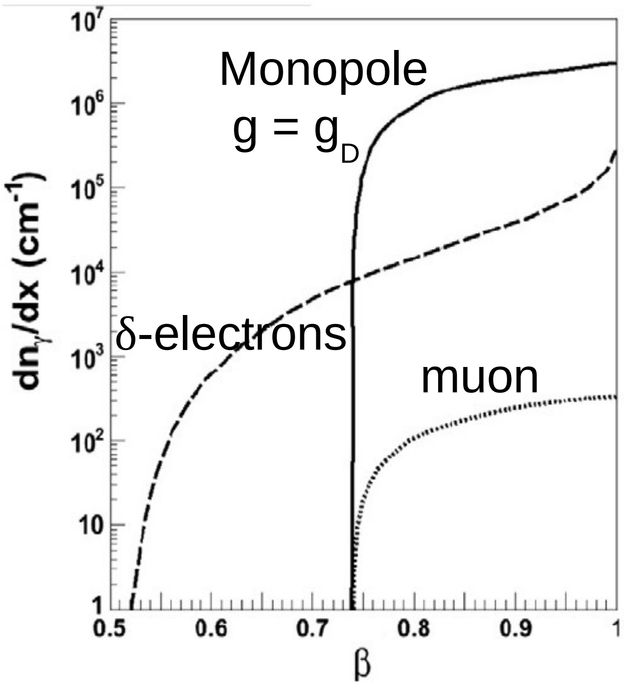
NEUTRINO OBSERVATORIES

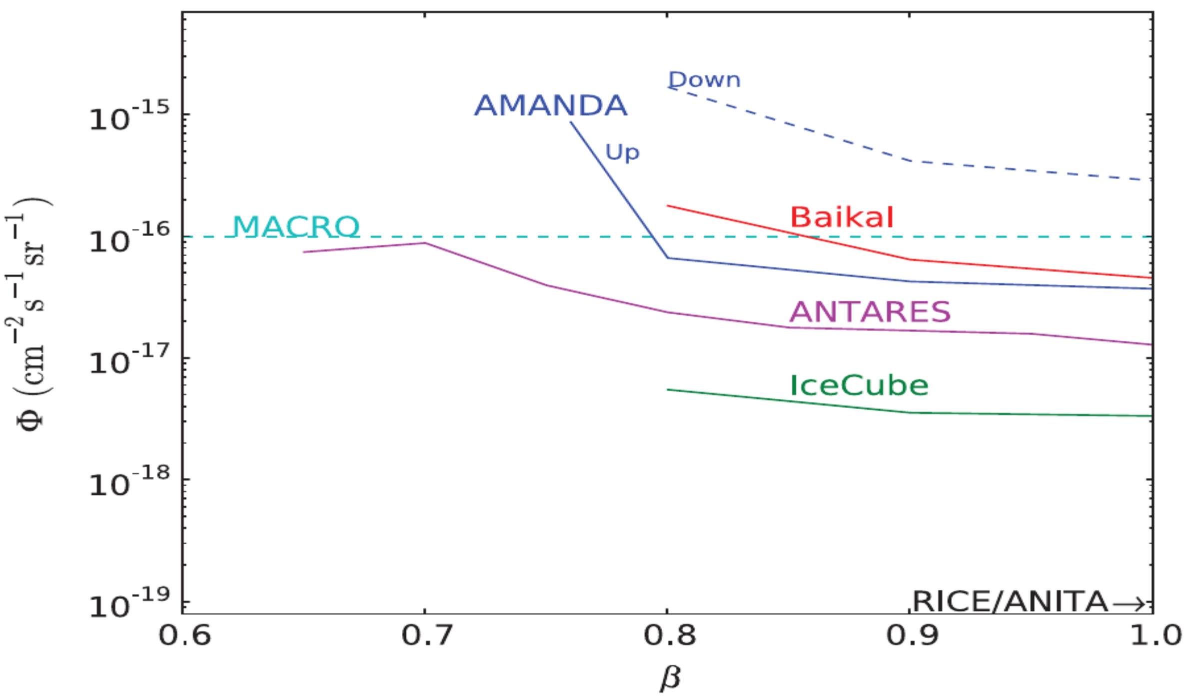
Upgoing monopole

(must traverse Earth)



PRD 78, 075031 (2008), arXiv:0806.2129
PRD 83, 023513 (2011), arXiv:1008.1282
Astropart. Phys. 35, 634 (2012), arXiv:1110.265
PRD 87, 022001 (2013), arXiv:1208.4861





ANCIENT MICA

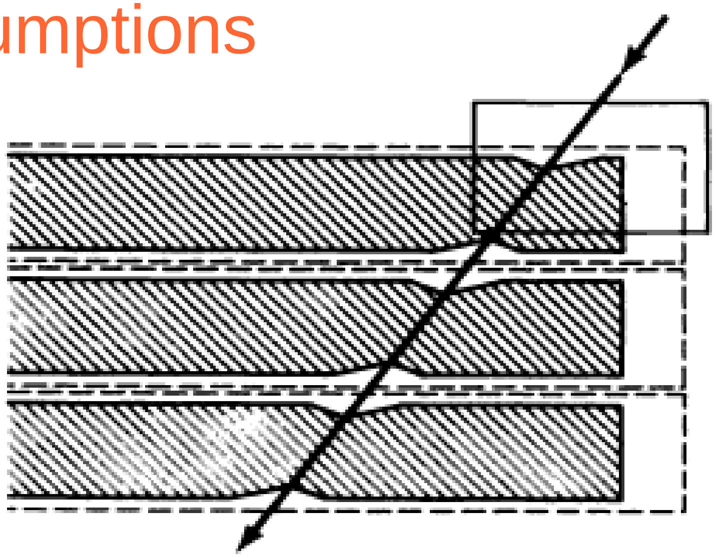
> 500 millions years exposure time!

Track formed only if:

- $g \geq 2\,g_D$ (perhaps relativistic $g = g_D$)
- Or, low-velocity ($\beta \sim 10^{-3}$) monopole captured a nucleus on its way through the rock

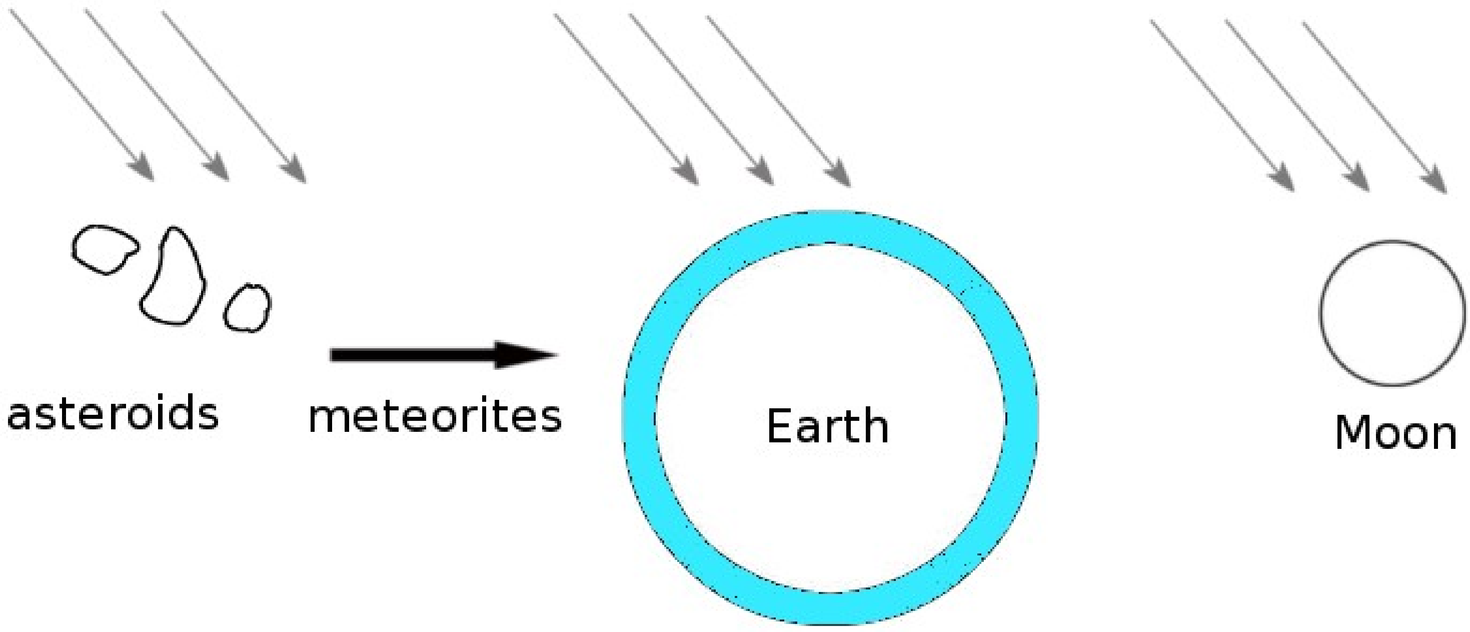
Under one of the above assumptions

$F < 5 \cdot 10^{-20}\ \mathrm{cm^{-2} s^{-1} sr^{-1}}$



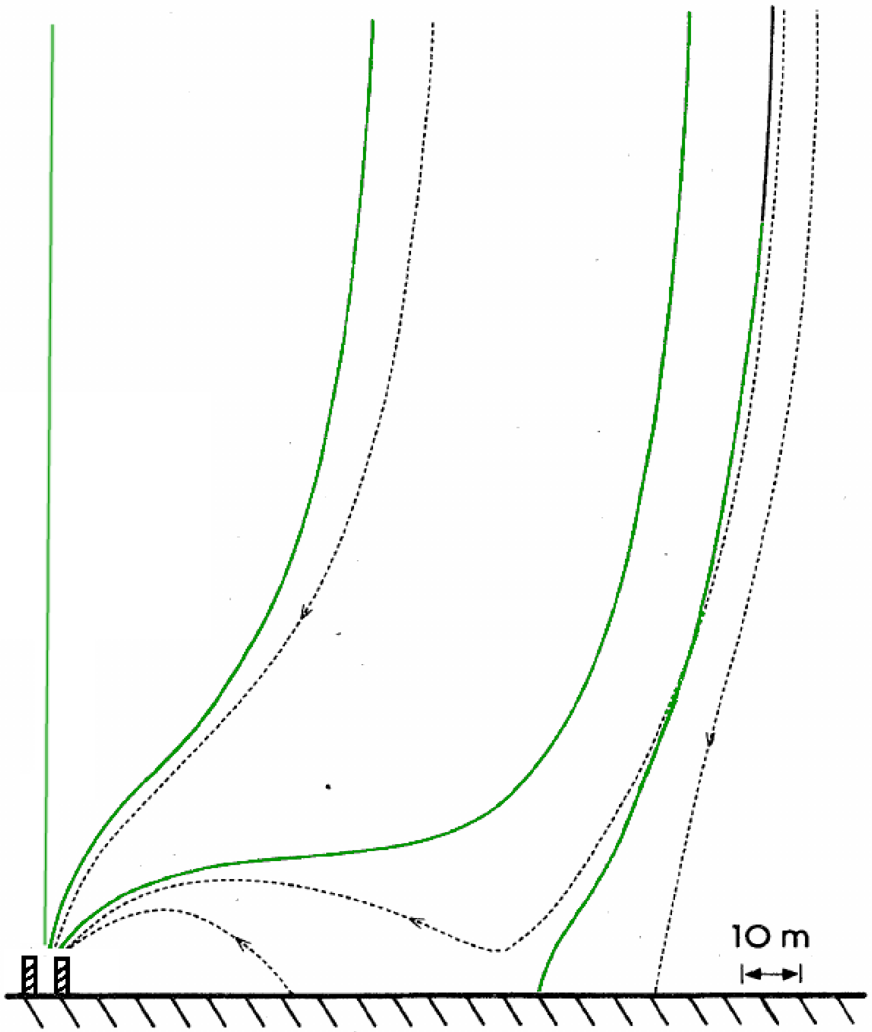
PR 184, 1398 (1969)
PRL 52, 1265 (1984)
PRL 56, 1226 (1986)
Europhys. Lett. 12, 25 (1990)

MATTER SEARCHES

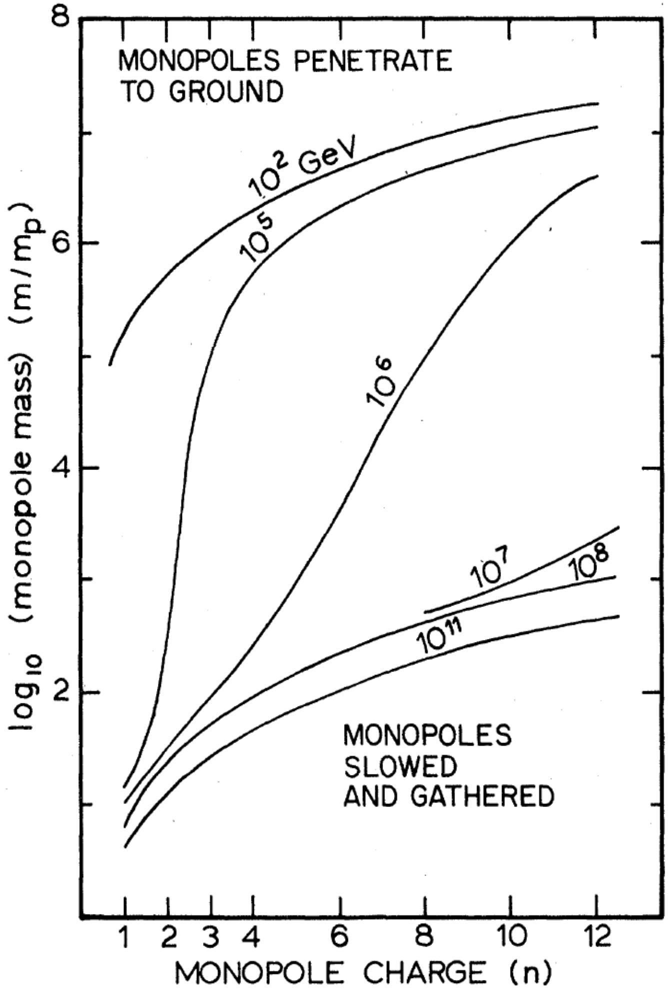


COLLECTION FROM ATMOSPHERE

50000 m² coverage

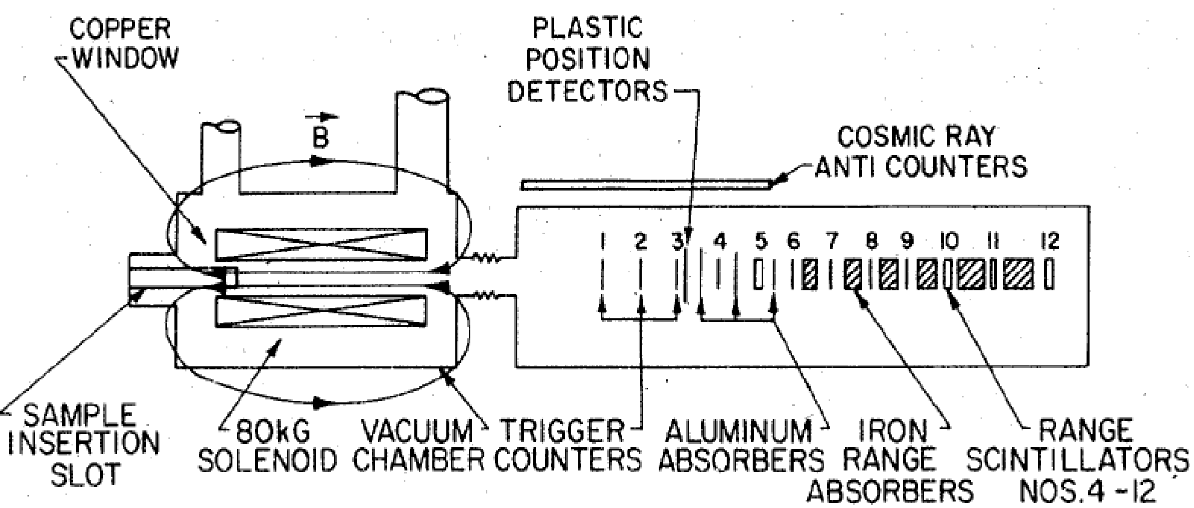


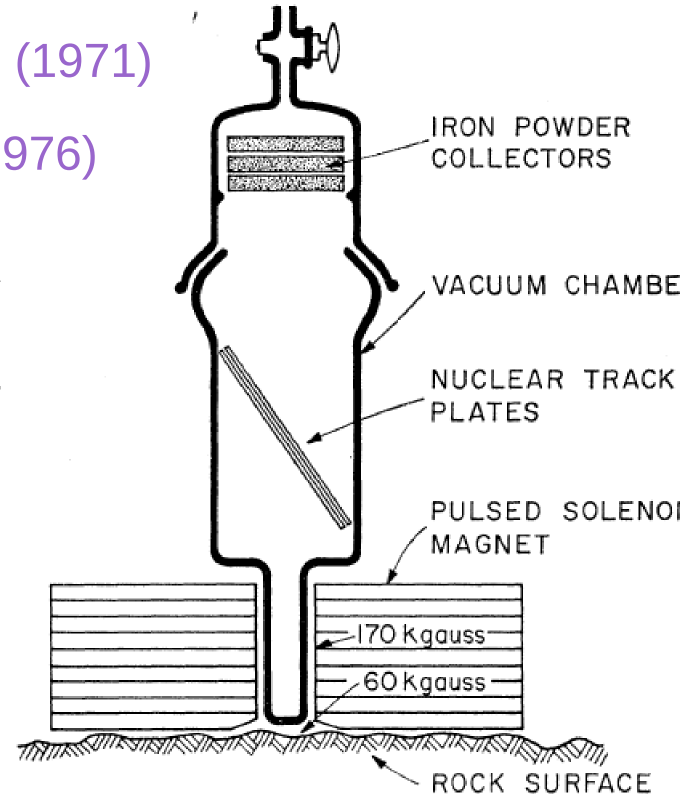
PR 83, 899 (1951)
PR 149, 1070 (1966)
PRD 24, 612 (1981)



EXTRACTION TECHNIQUE

- Meteorite fragment Nucl. Phys. 49, 87 (1963)
- Magnetite and meteorite 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)

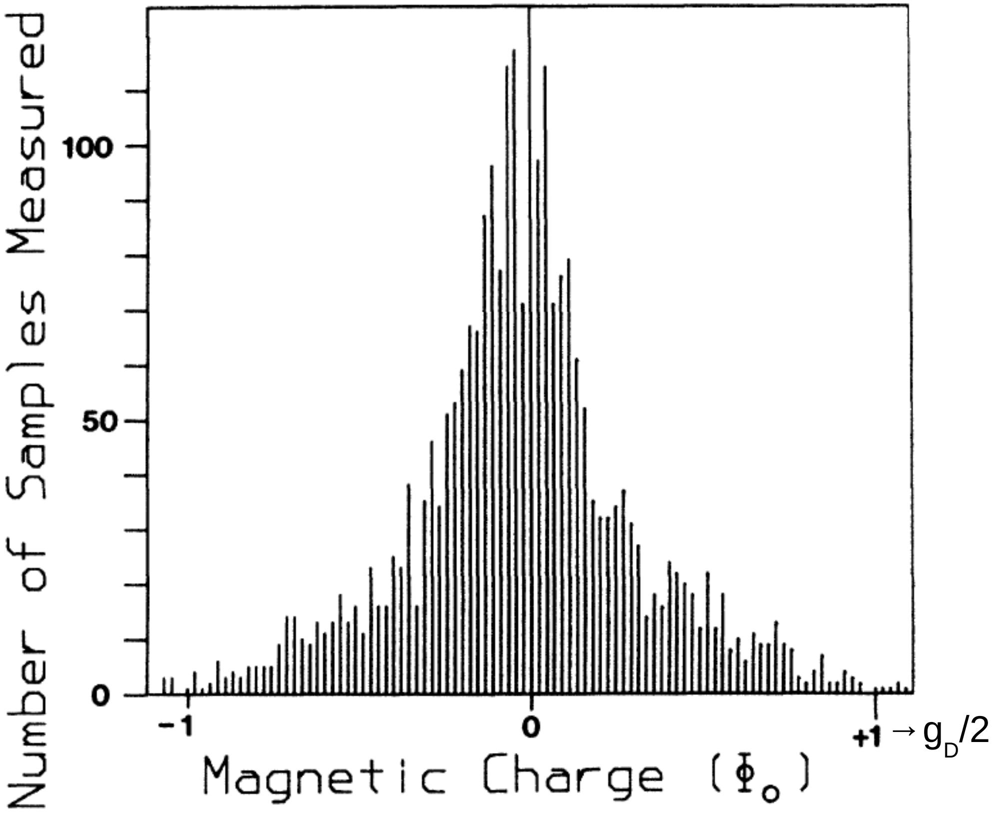




LARGE-SCALE INDUCTION SEARCH

- 180 kg sea water
- 145 kg manganese nodules
- 498 kg deep schist at 25 km depth
- 20 times more material than all previous searches together
- Robust technique

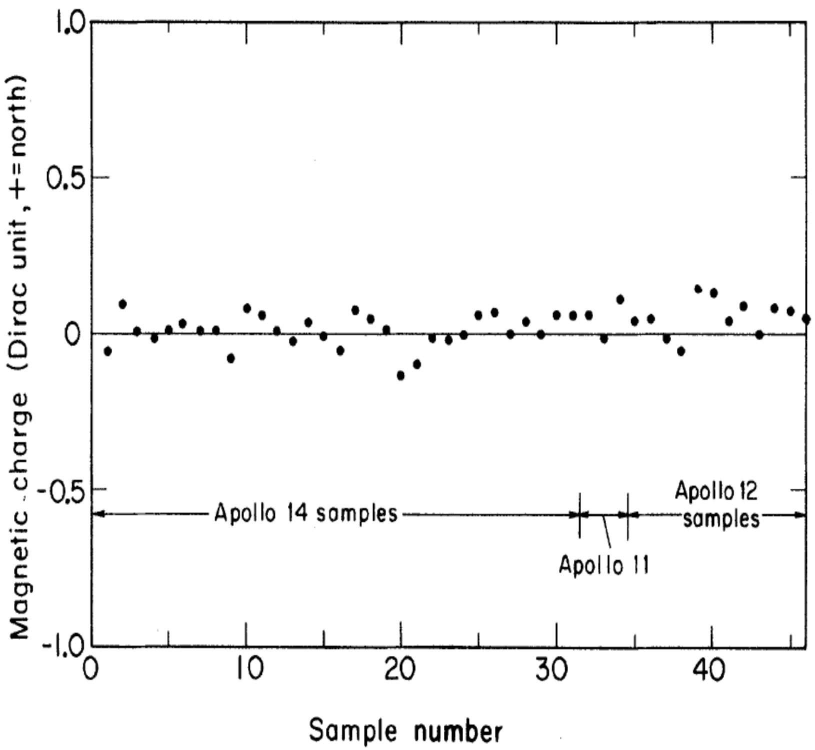
PRA 33, 1183 (1986)

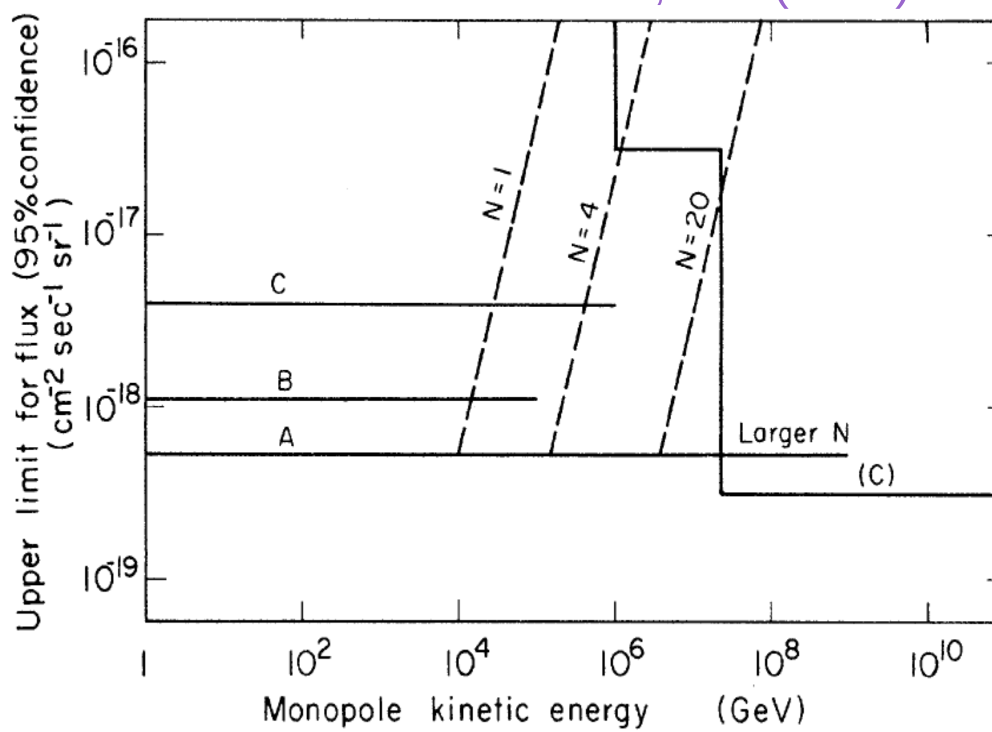


MOON ROCKS

- 48 kg returned from Apollo missions
- 4 billions years exposure
- No atmosphere and no magnetic field → robust assessment of monopole fate after stopping (few meters depth)

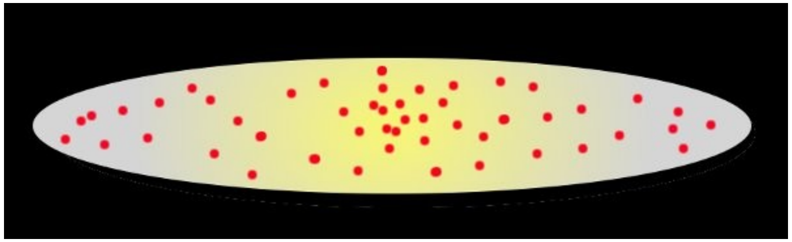
PRD 4, 3260 (1971)
PRD 8, 698 (1973)



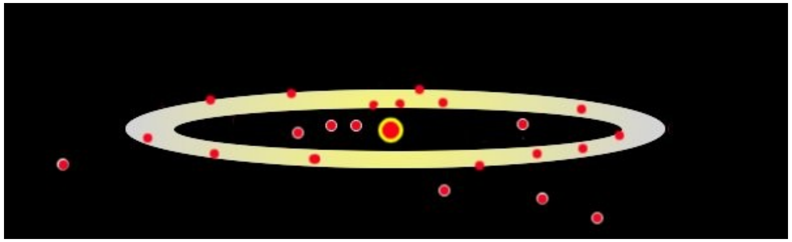


STELLAR MONOPOLES

Cloud

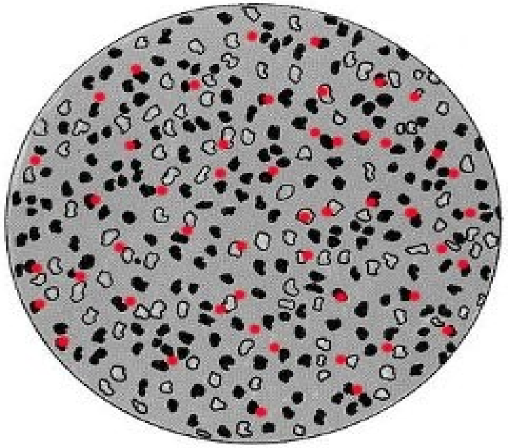


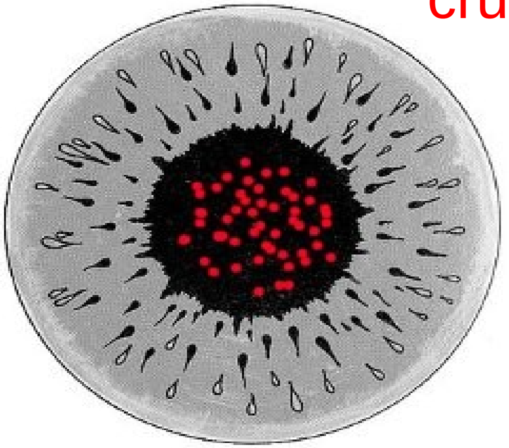
Planetary System



Heavier than the heaviest nuclei → absent from crust

Planetary differentiation





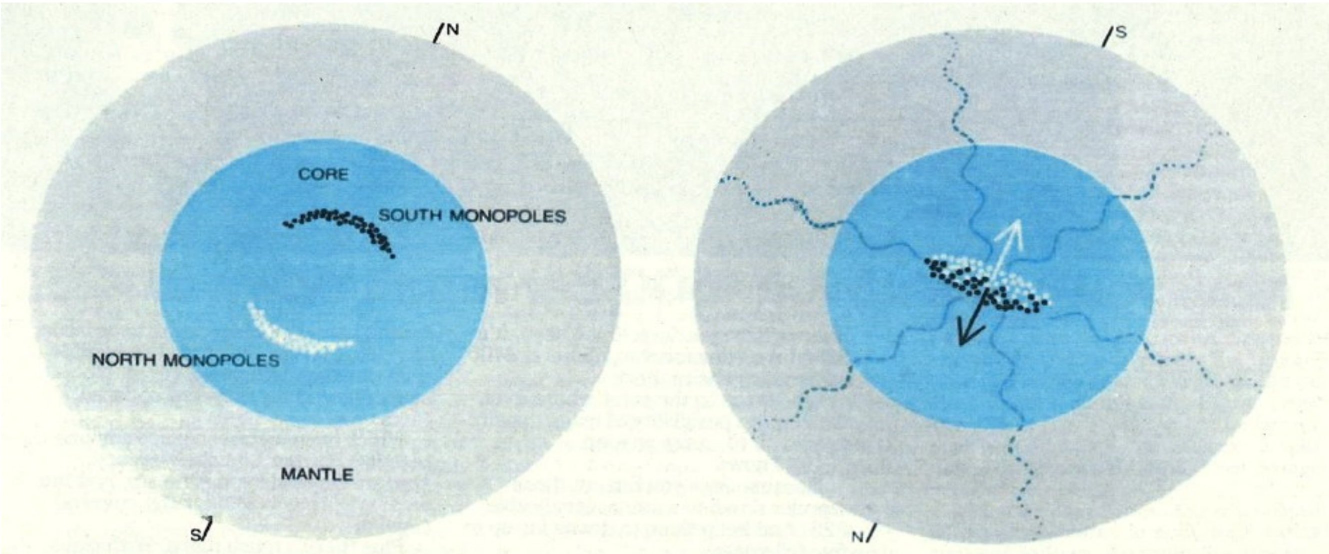
EARTH HEAT

Heat from monopole-antimonopole annihilations during geomagnetic reversals

→ limit $\rho < 10^{-4}$ mon./g Nature 288, 348 (1980)

Must assume mass ~10^{16} GeV and:

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

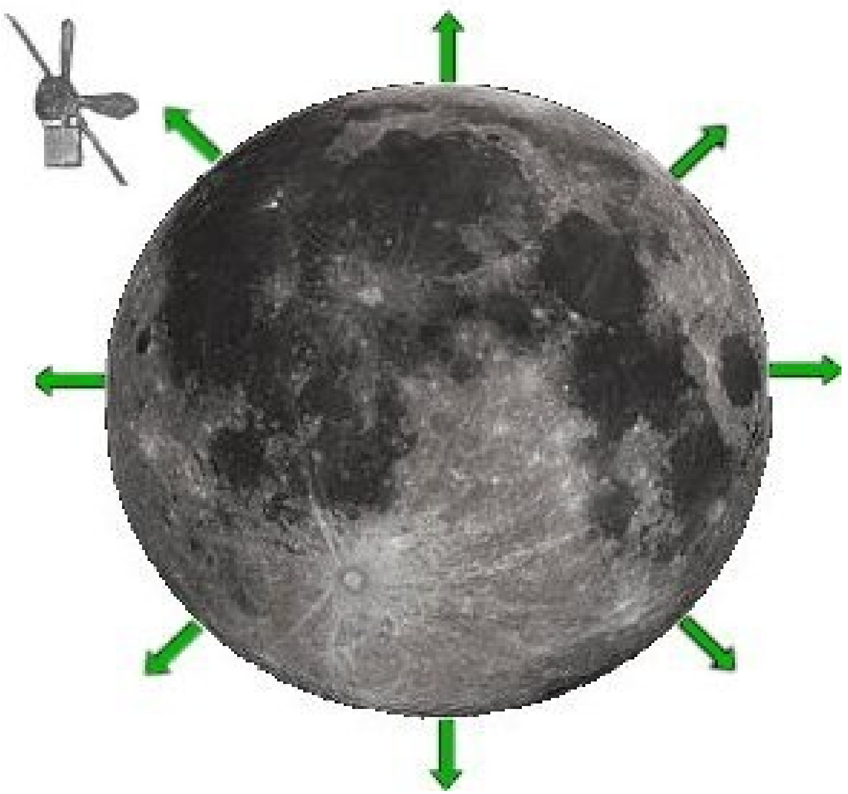


MOON FIELD

Magnetometer observations aboard Explorer 35 orbiting the Moon: No radial component

→ limit $\rho < 4 \cdot 10^{-9}$ mon./g PRD 27, 1525 (1983)

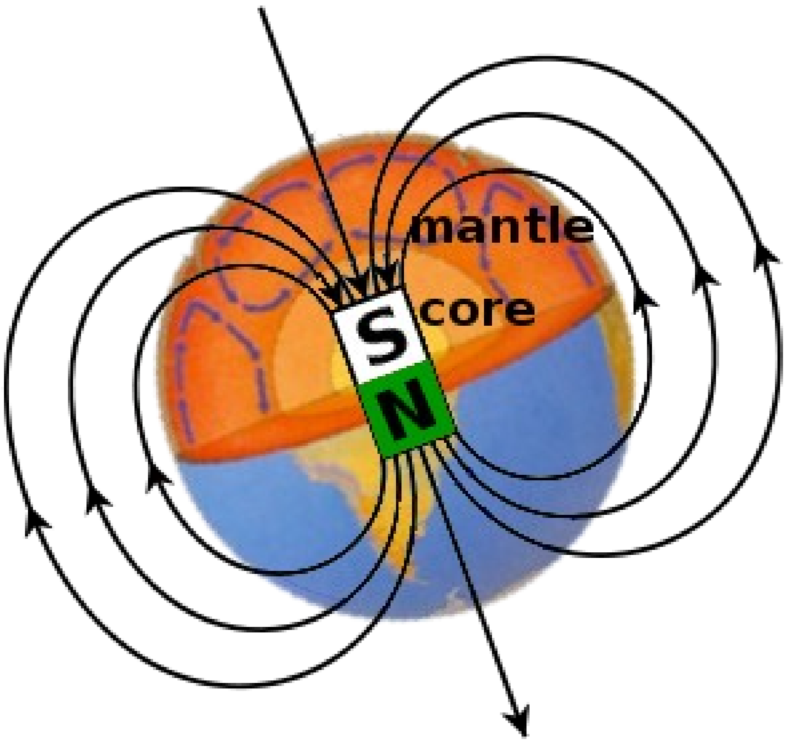
Must assume monopoles predominantly of one sign



METEORITES

- 331 kg of rocks with induction technique
  (meteorites, ferromanganese nodules, iron ores, blueschists, sediments, kimberlites, chromates)
- 112 kg of meteorites   Phys. Rev. Lett. 75, 1443 (1995)
  - ~100 kg chondrites → stellar monopoles!
  - Masses up to 10^{17} GeV, beyond which monopoles might be dislodged by meteor impact

POLAR VOLCANIC ROCKS

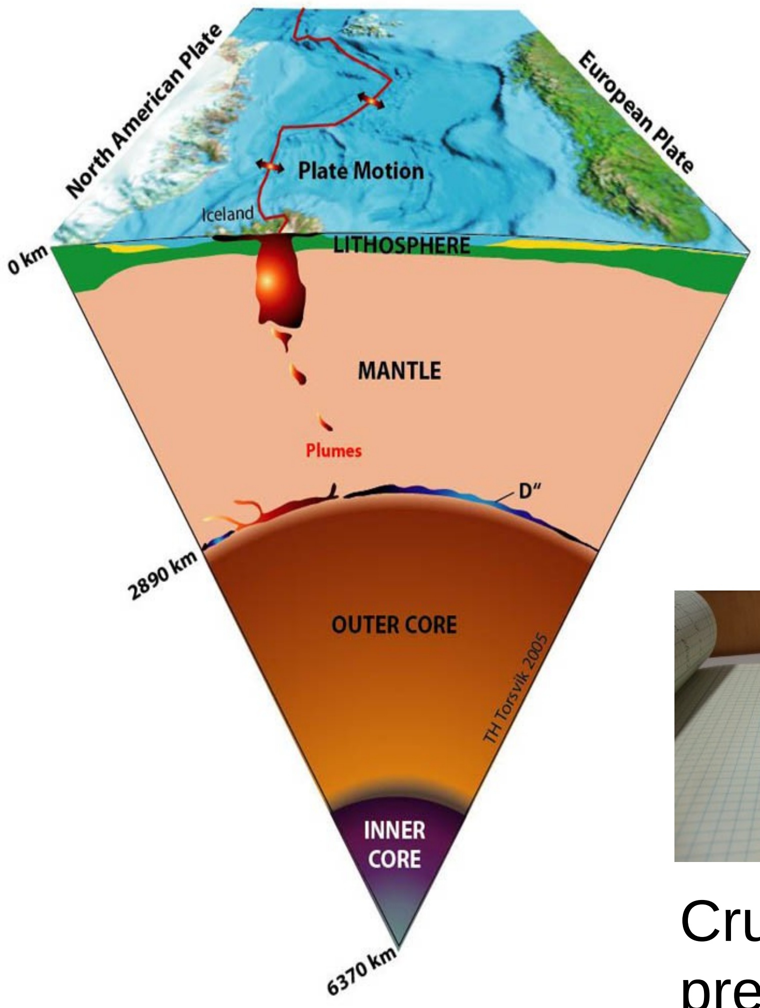


For Dirac charge (*n* = 1), magnetic force exceeds gravitational force above core-mantle boundary for:

$M < 4{\cdot}10^{14}$ GeV

Over geologic time, accumulation in the mantle beneath the geomagnetic poles

POLAR ROCKS – SAMPLES

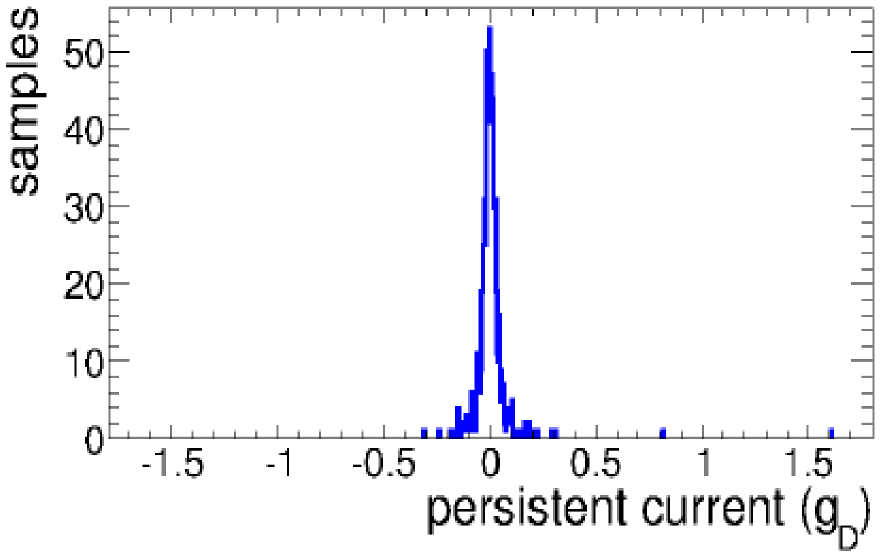


High latitude (>63°), mantle derived

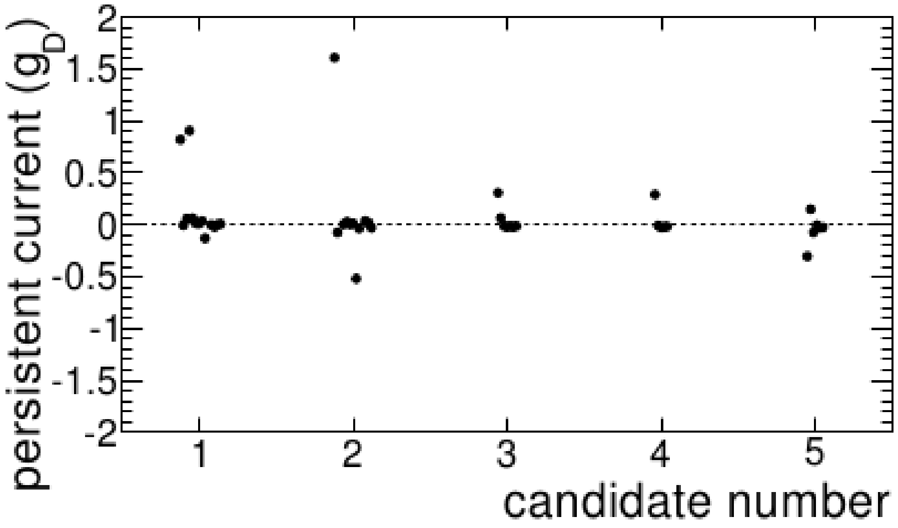
- Hotspots
- Mid-ocean ridges
- Large igneous provinces
- Isotopic content indicating deep origins

Crushed to reduce magnetisation for precise magnetometer measurement

POLAR ROCKS – RESULTS



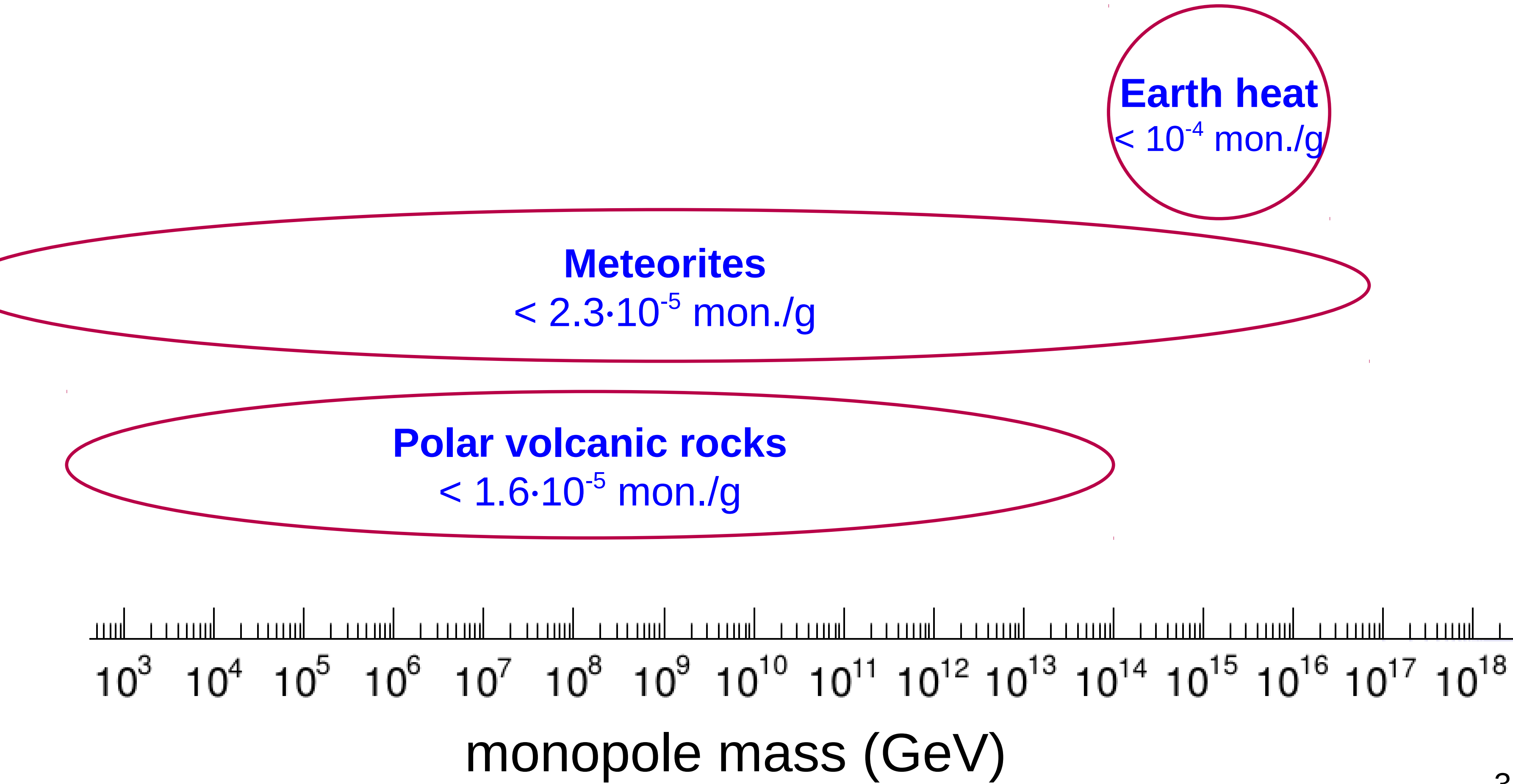
Phys. Rev. Lett. 110, 121803 (2013)



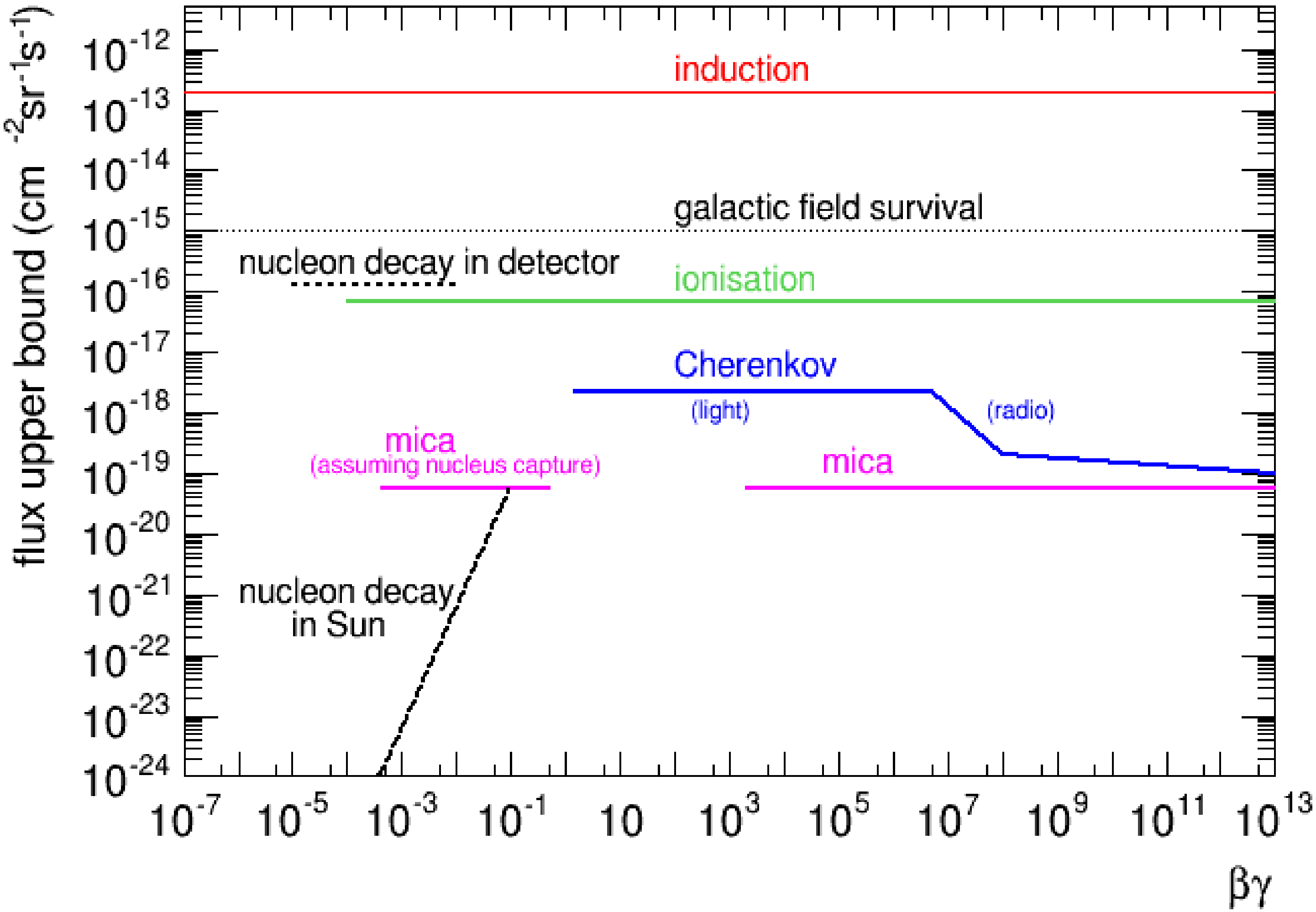
No monopoles found in 24 kg of polar volcanic rocks

– In simple model, translates into limit of less than 1.6 monopole per 100 kg in the Solar System

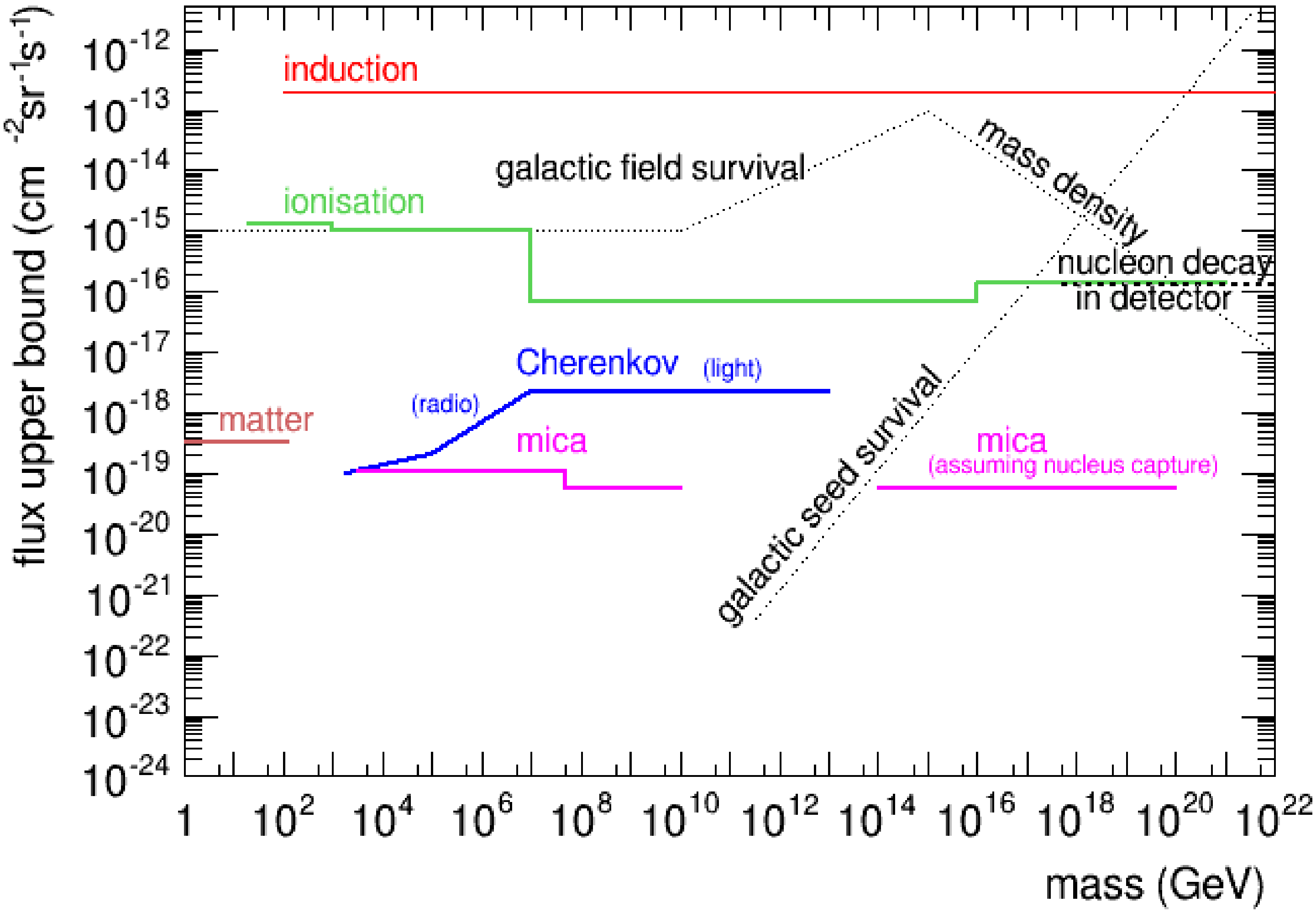
LIMITS ON STELLAR MONOPOLE DENSITY IN THE SOLAR SYSTEM



COSMIC FLUX LIMITS – SUMMARY 1



COSMIC FLUX LIMITS – SUMMARY 2



SUMMARY

Magnetic monopoles are fundamental, well-motivated objects

80 years after the Dirac argument, searches for monopoles are still very much alive

- In-flight detection with ATLAS / MoEDAL
- Trapping arrays / beam pipes
- Cosmic induction / ionisation / Cherenkov arrays
- Fossile tracks in mica
- Monopoles in sediments / rocks / meteorites

CAN WE DO BETTER?

Future Circular Colliders

- 10^{12} Z bosons → indirect effects M <~ 10 TeV
- 100 TeV pp collider → direct searches M <~ 45 TeV

Acoustic neutrino detectors

- 100 km^3 → gain factor 20

Modern scanners with sub-micrometer precision at >100 cm^2 per hour

- 10 km^2 NTD array → gain factor 10
- 100 m^2 of ancient mica → gain factor 1000

Stellar monopoles

- 1 ton of polar rocks → gain factor 40
- Comet / asteroid fragments gathered in space missions

Extra slides

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:

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

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

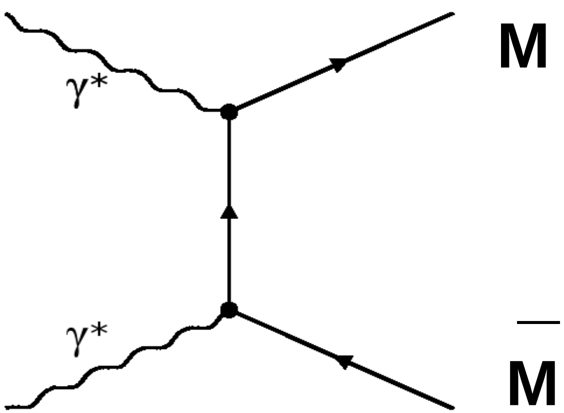
Monopole production

EM coupling constant for Dirac charge = 34.25

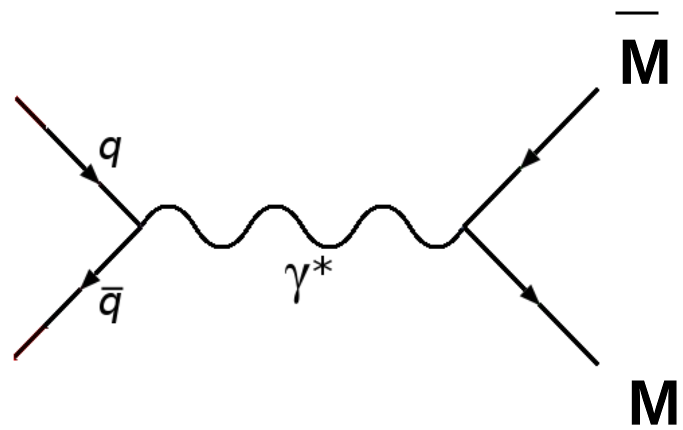
→ non-perturbative dynamics, no reliable cross sections and kinematics!

“Natural” benchmark models:

photon fusion



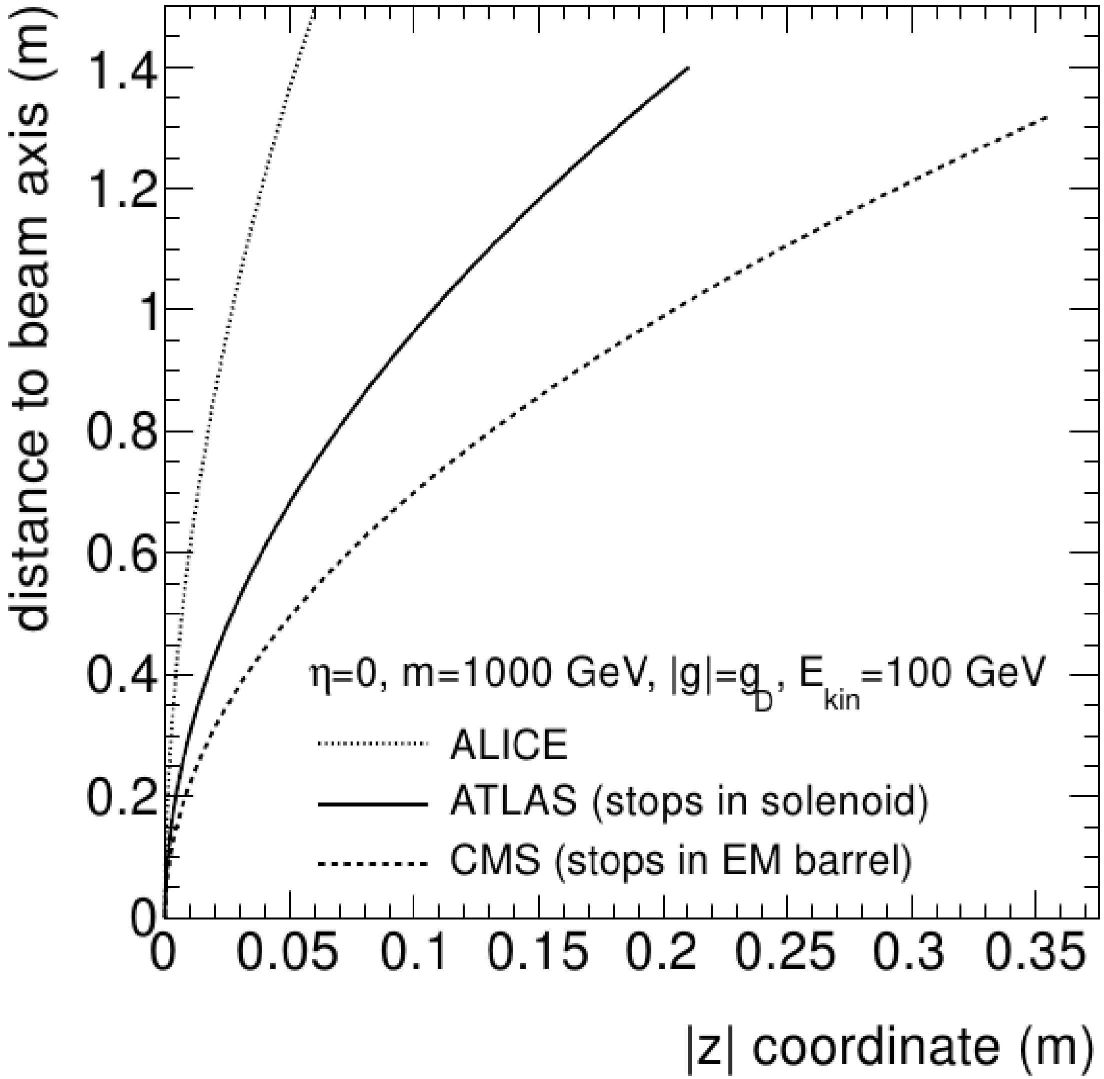
Drell-Yan



Remark: magnetic charge conservation prescribes that monopoles are **stable** and **produced in pairs**

Monopole bending

arXiv:1112.2999



Acceleration along magnetic field:

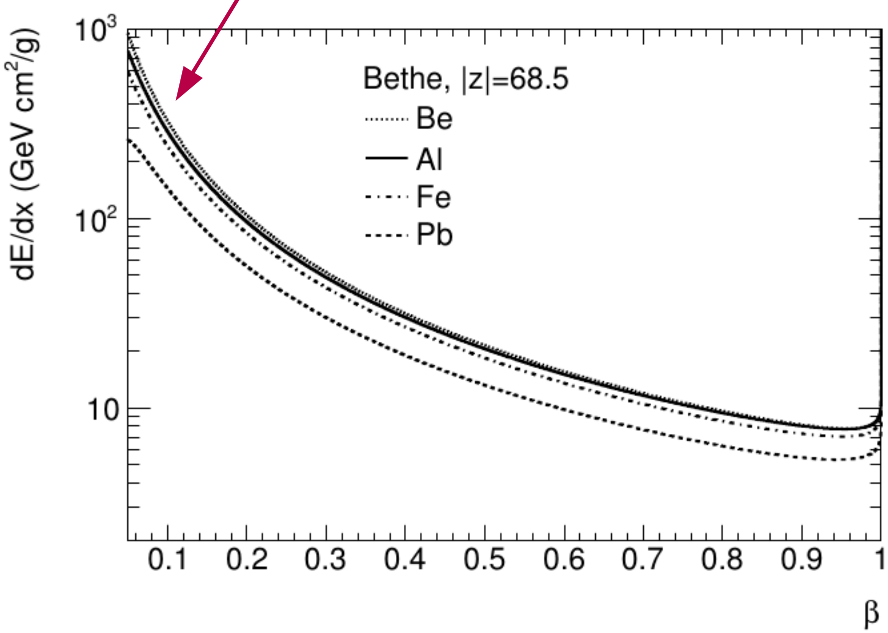
$$F_m = q_m \cdot B$$

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

Monopole ionisation energy loss

Electric

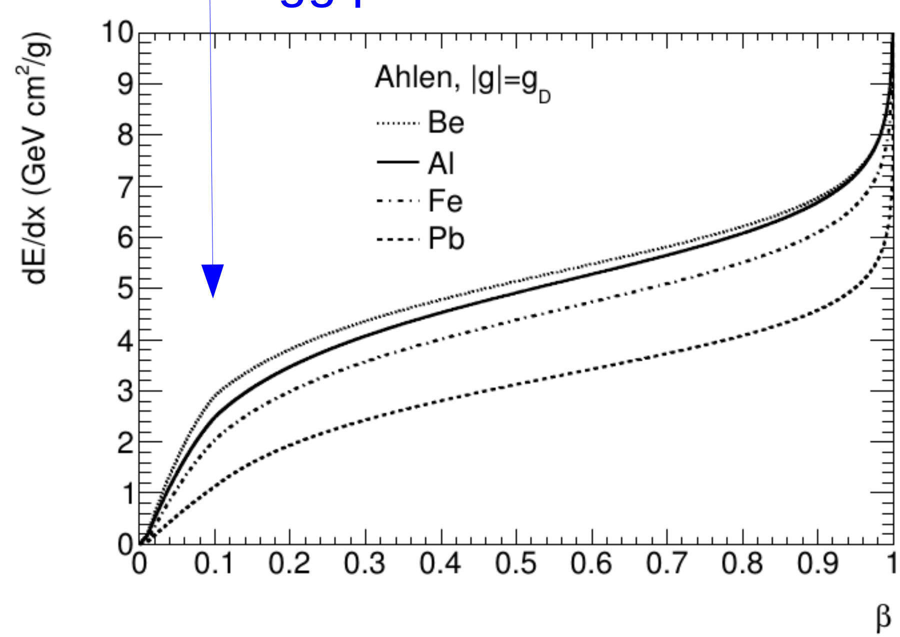
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2\right]$$



Magnetic

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

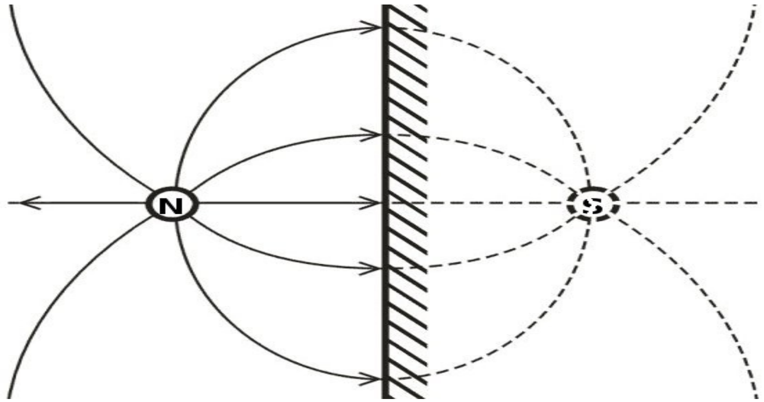
No Bragg peak!



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

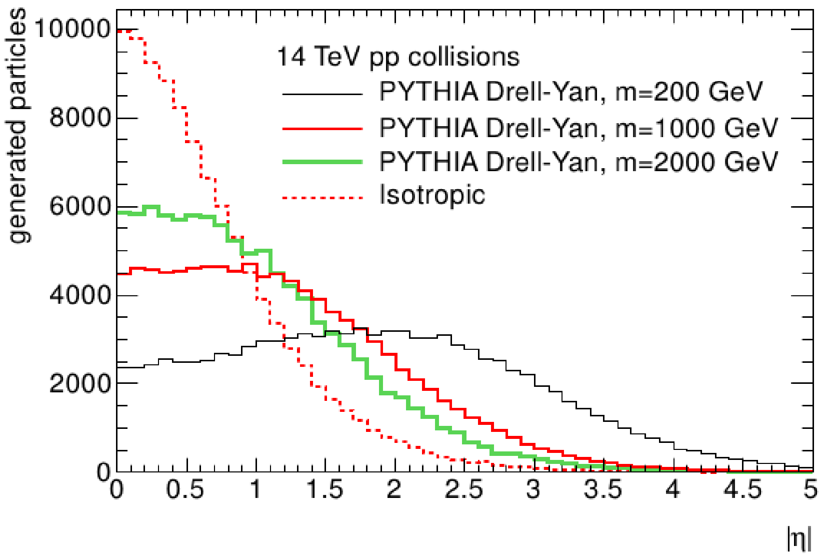
Monopole binding in matter

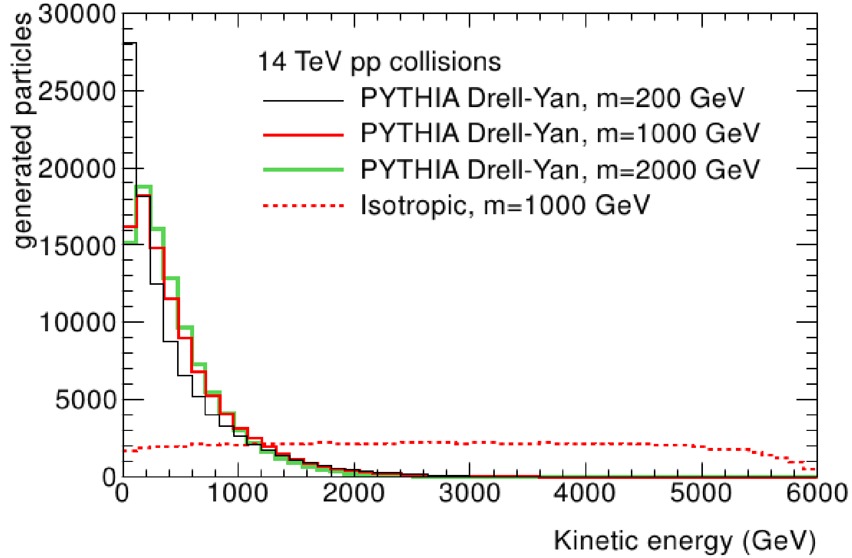
- **To atoms and molecules**
  - Binding energies of the order of a few eV
- **To nuclei with non-zero magnetic moments**
  - Binding energies of the order of 200 keV
- **At the surface of a ferromagnetic**
  - Image force of the order of 10 eV/Å
  - **Robust prediction** (classical)

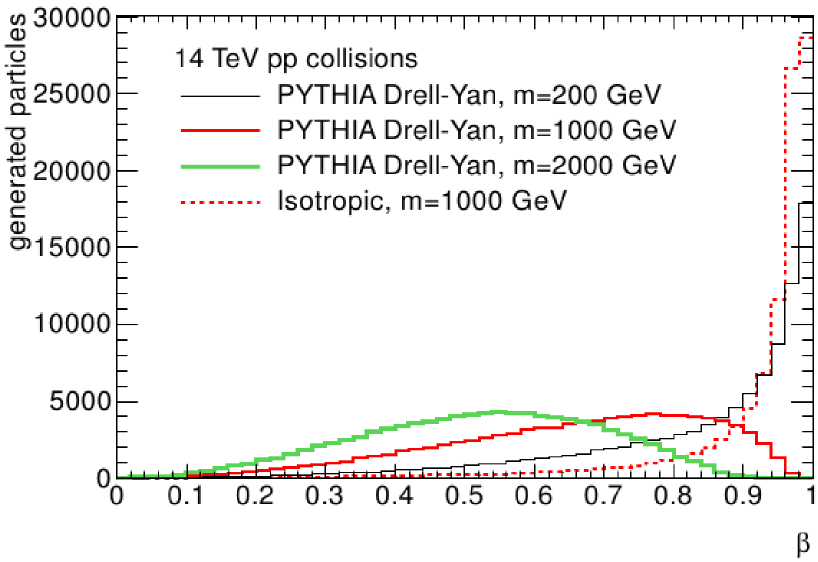


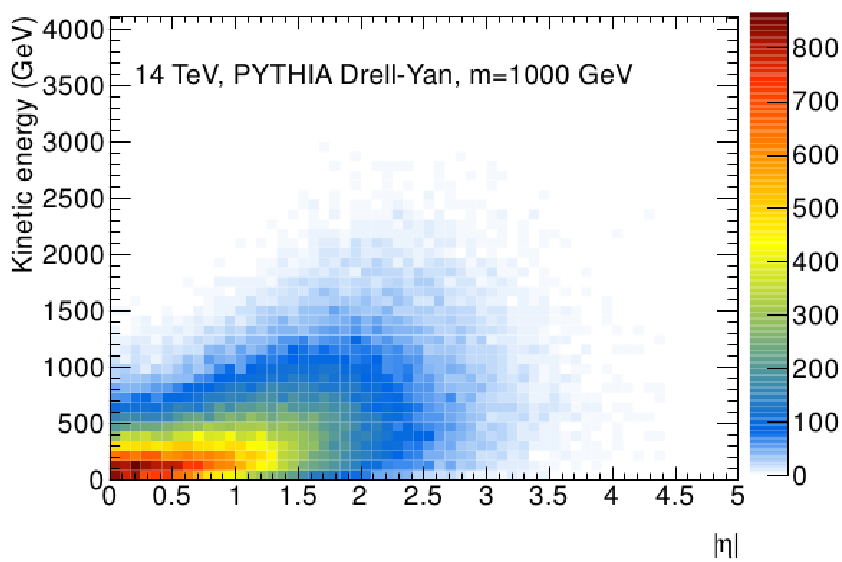
Monopole production kinematics

arXiv:1112.2999



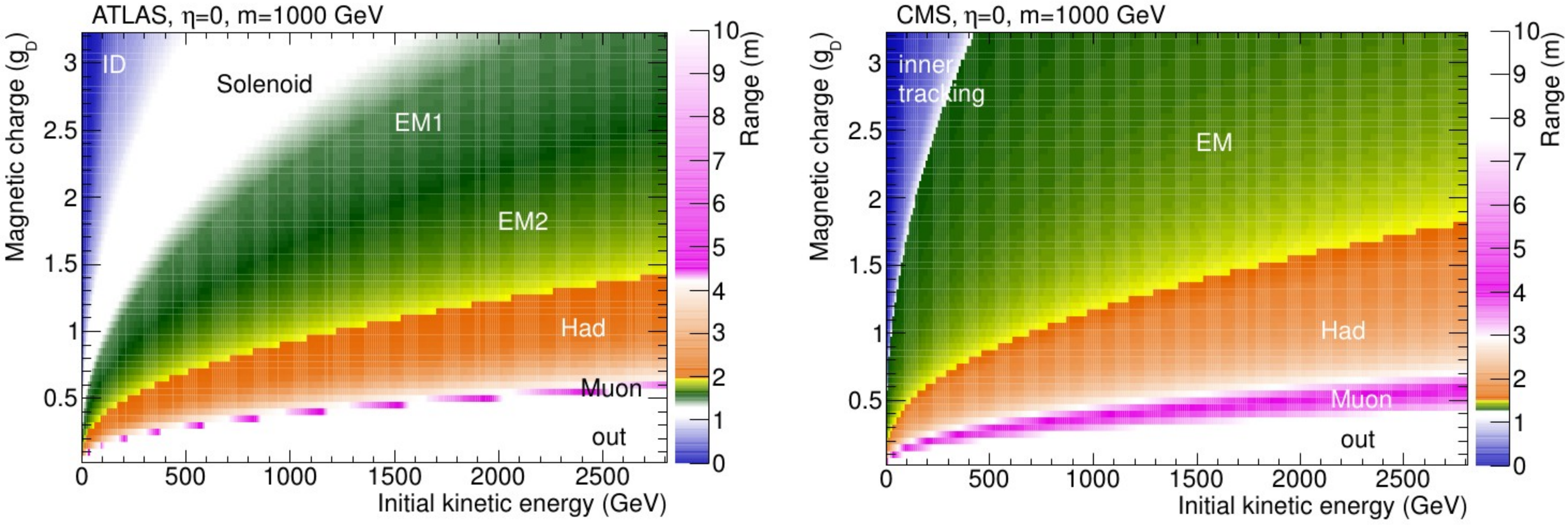






Range of monopoles in ATLAS and CMS

arXiv:1112.2999 (2012)

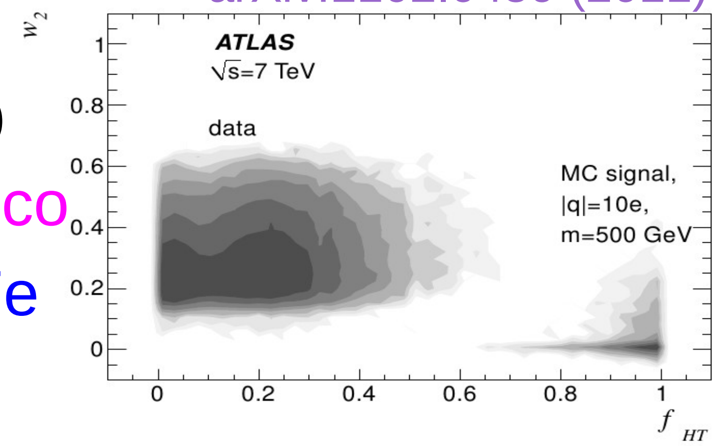


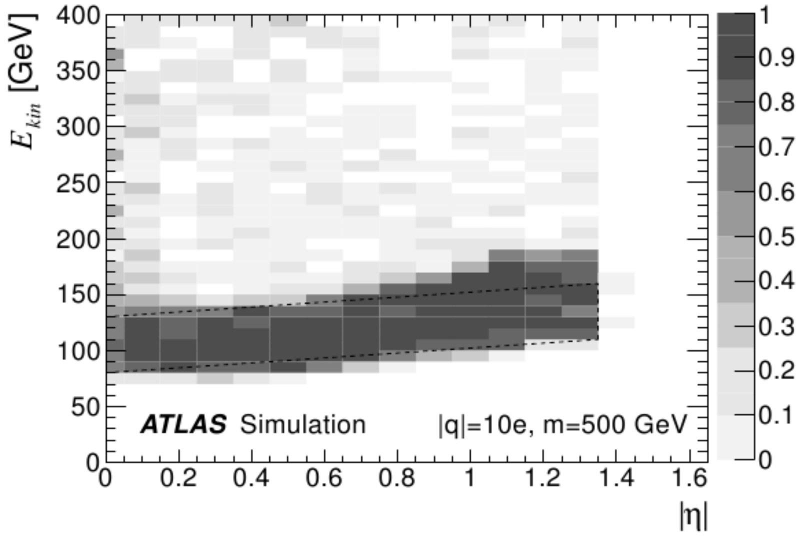
ATLAS search multiply-charged particles

arXiv:1102.0459 (2011)

First HIP search at the LHC

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



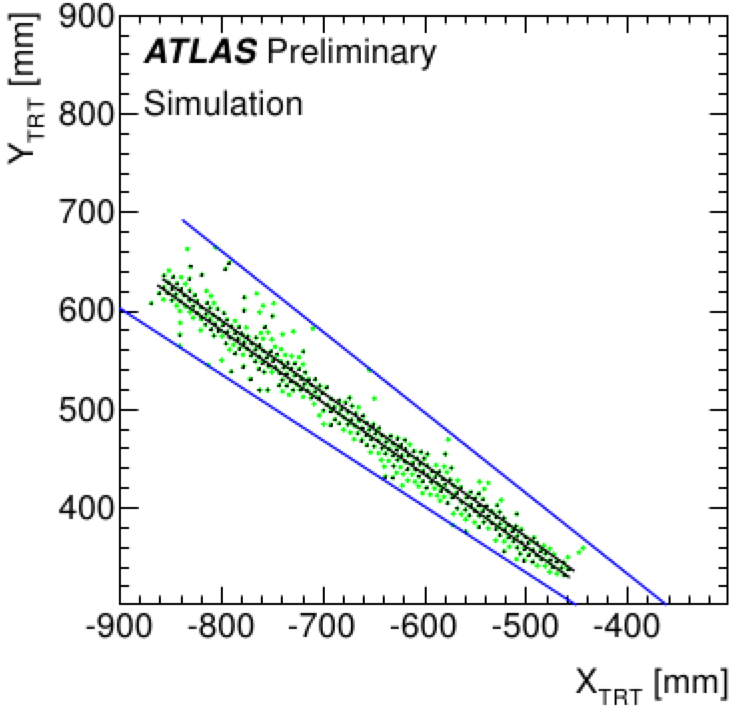


Model-independent approach:

1-2 pb limits set in well-defined kinematic ranges

ATLAS monopole search – principle

ATLAS-CONF-2012-062

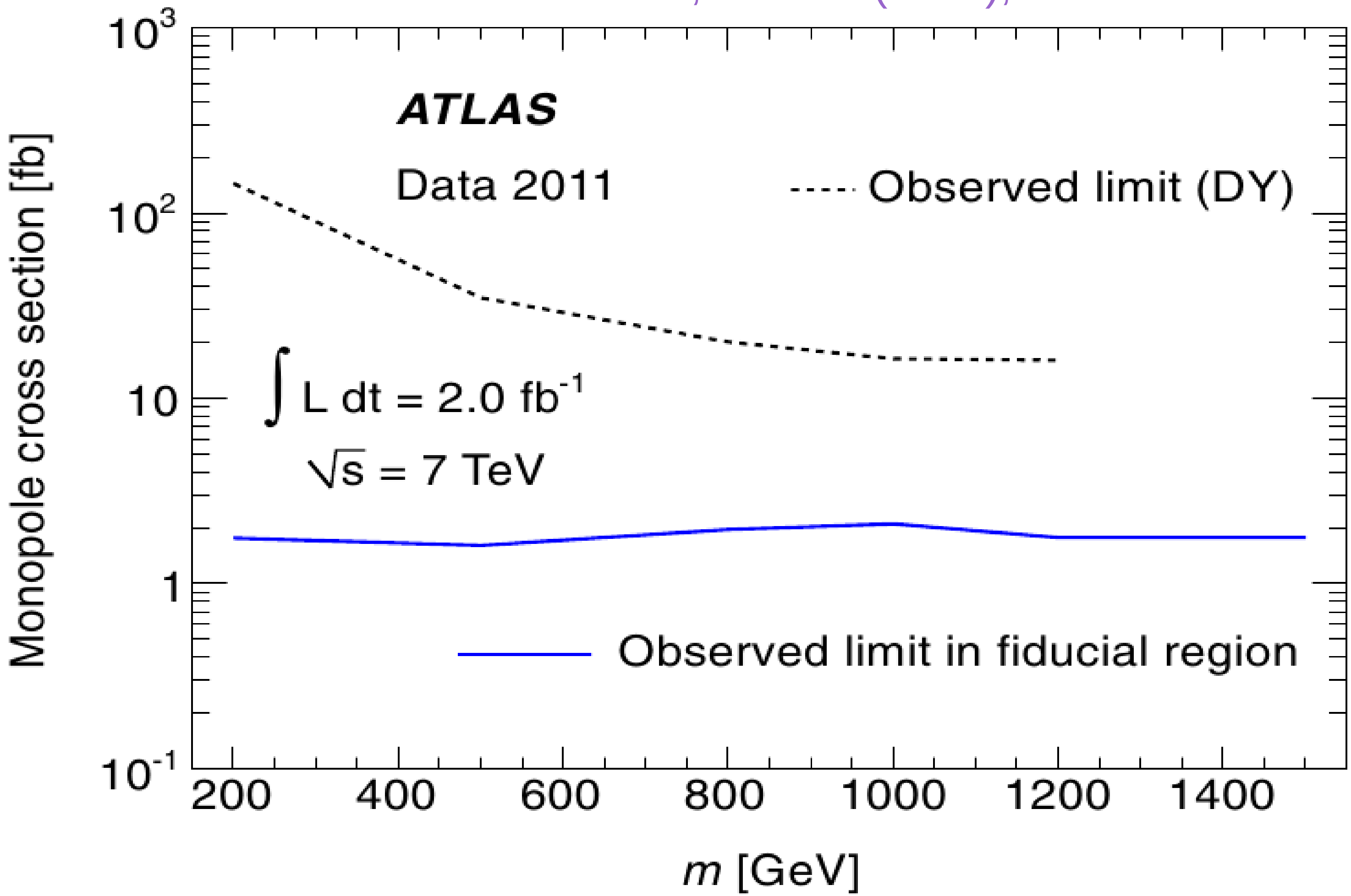


- Data from 2011 (2 fb^{-1})
- Standard EM trigger
- Special tracking
  - Count TRT hits in window around EM cluster
  - Robust against delta-electrons and anomalous bending
- Interpretation for magnetic monopole with minimum charge ($|g| = g_D$)
  - Applying HIP correction in LAr
  - Simulating monopole dE/dx and trajectory in Geant4

ATLAS monopole search – results

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

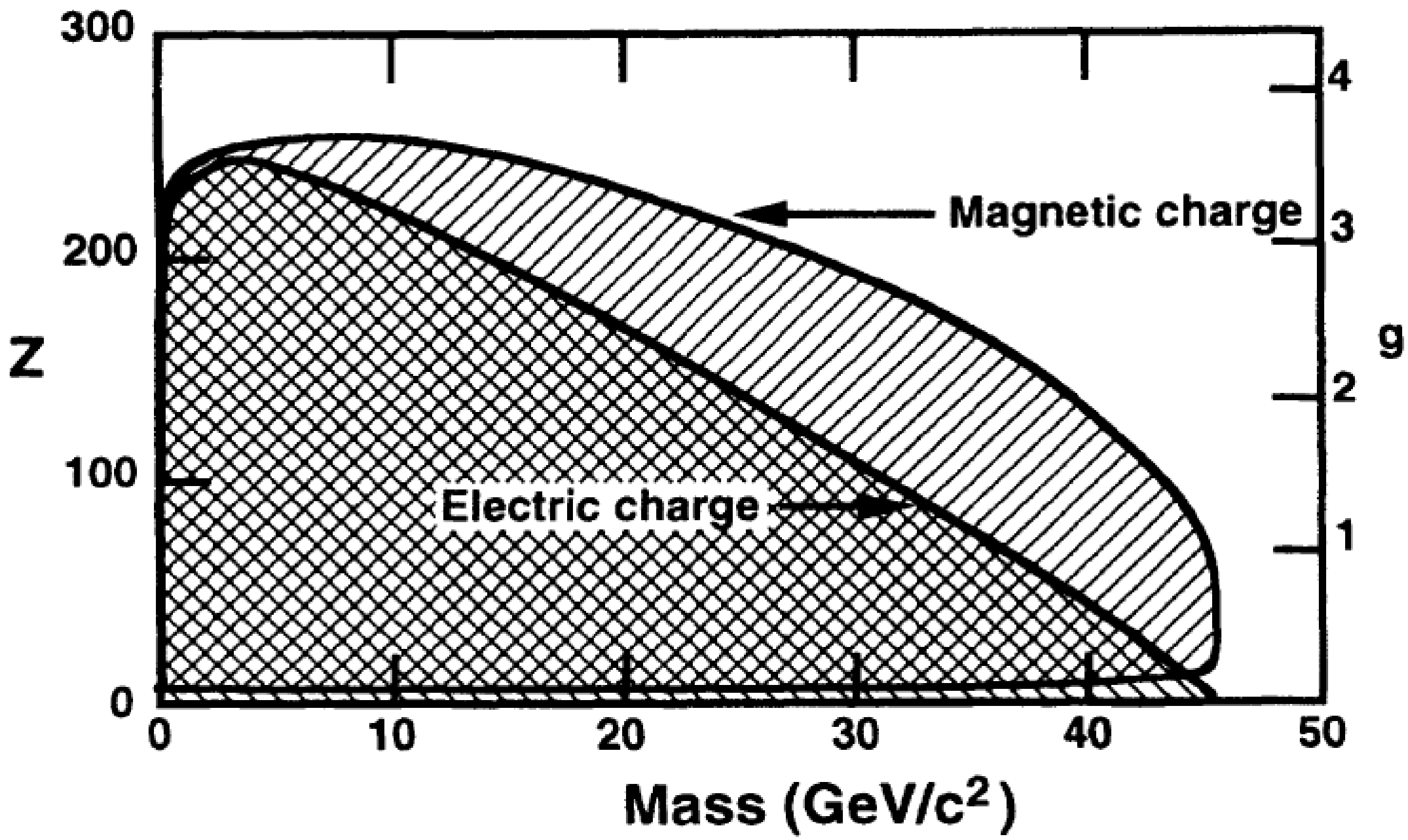
PRL 109, 261803 (2012), arXiv:1207.6411



LEP1, track-etch

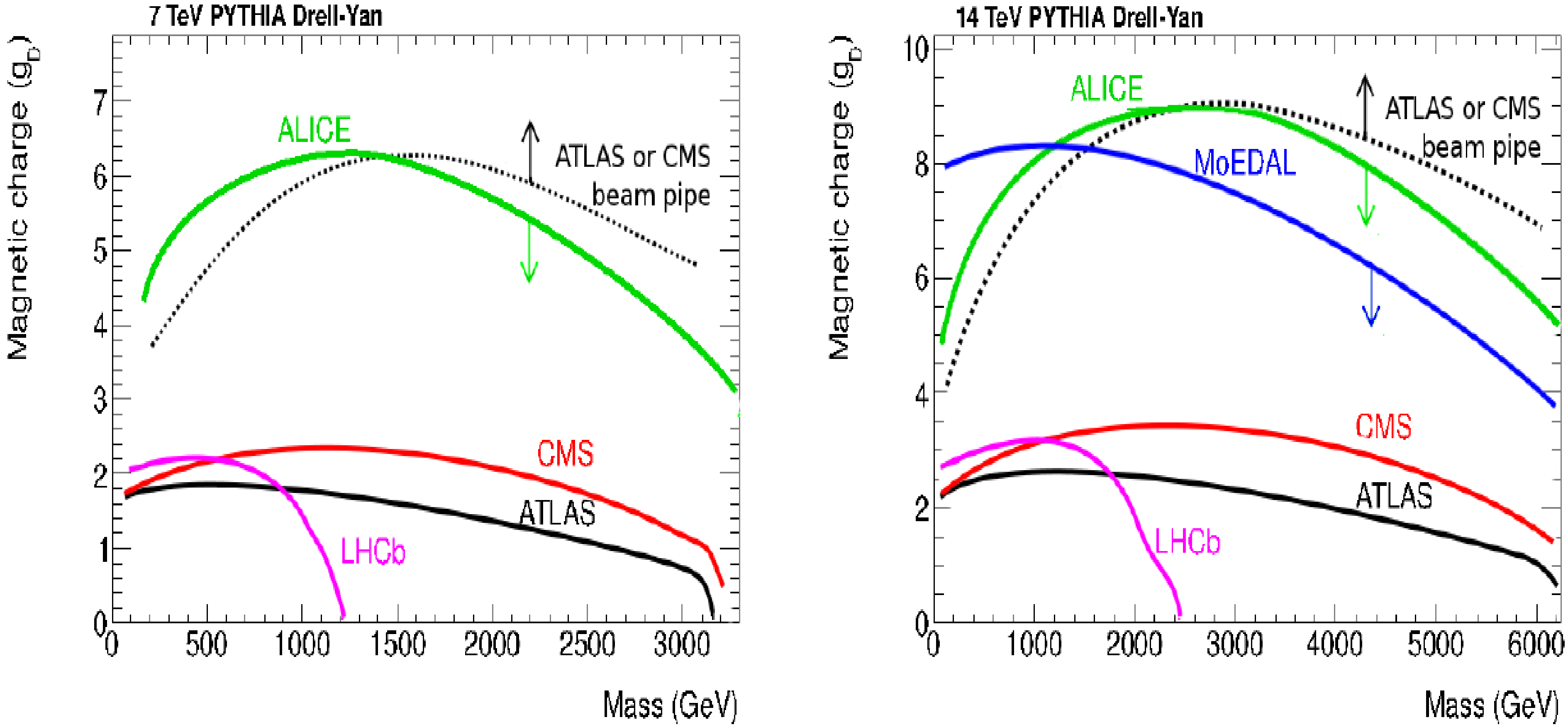
- Plastic detectors surrounding I5 interaction point
- 0.3 pb limit (up to 45 GeV HIPs)

Phys. Rev. D 46, R881 (1992)



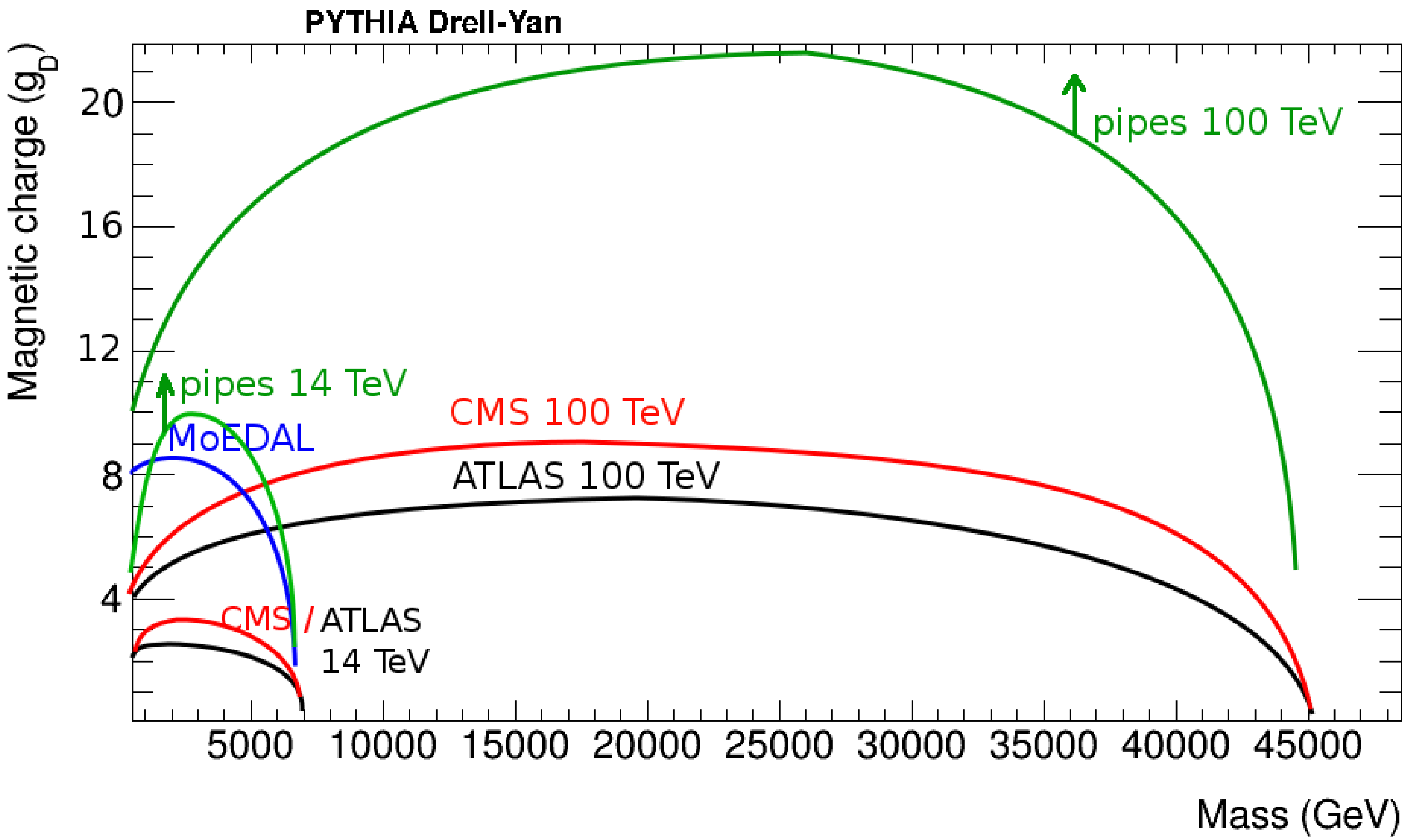
LHC reach in mass and charge

arXiv:1112.2999 (2012)

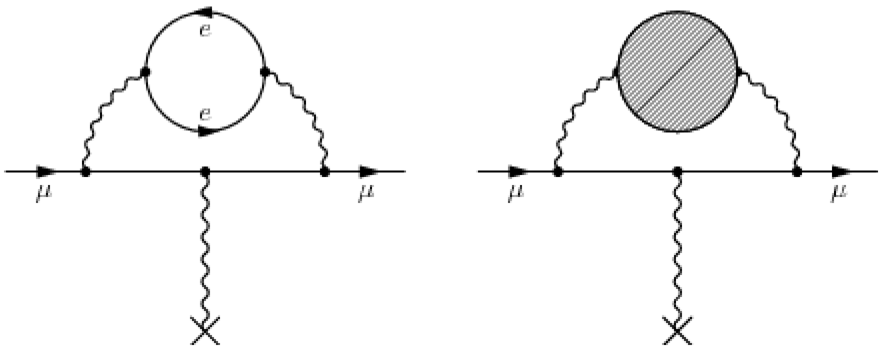


Monopoles in 100 TeV pp collisions

Contours with >5% acceptance

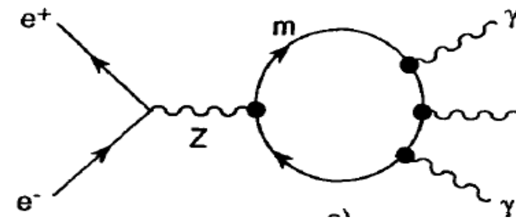


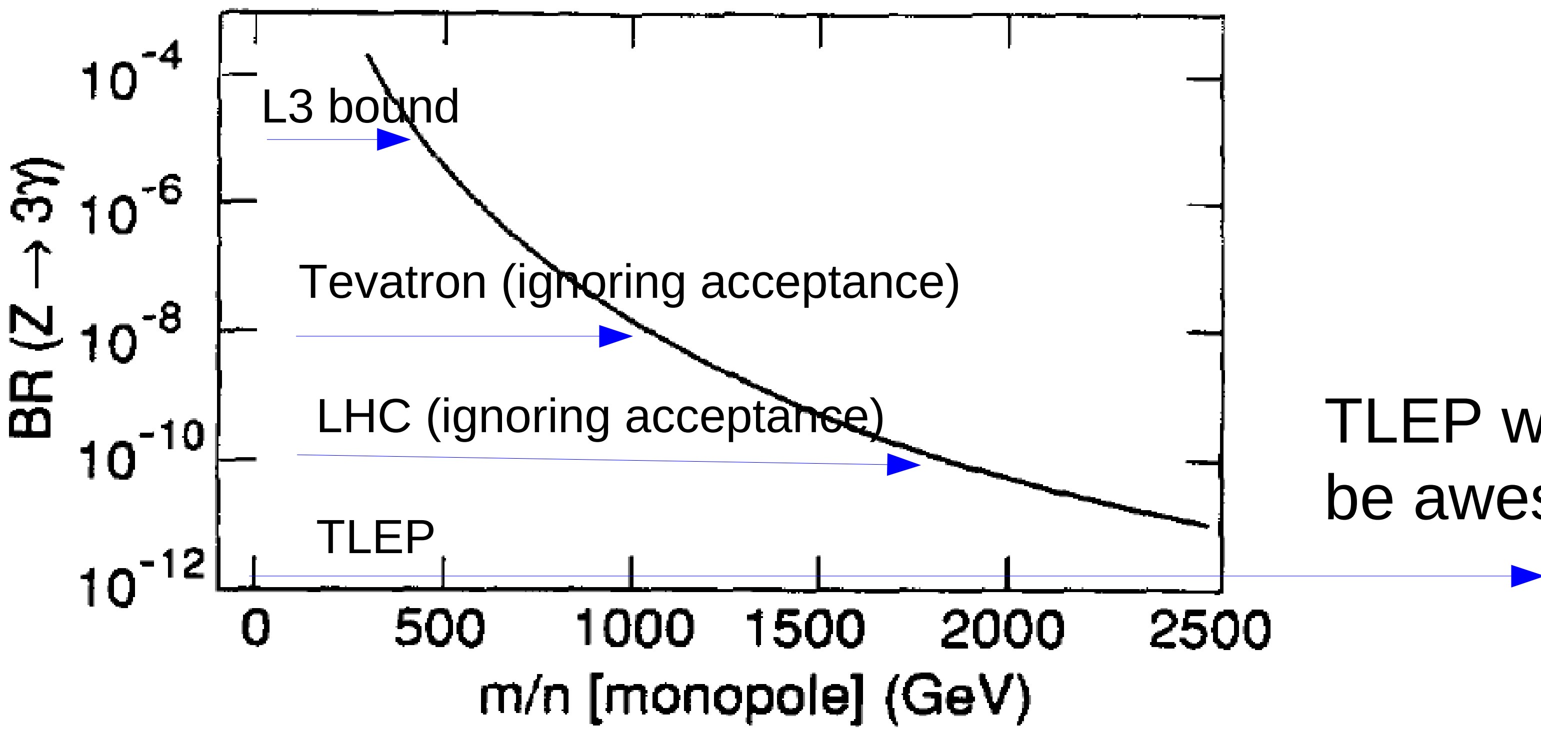
Muon anomalous magnetic moment (*g-2*)



- An example of a virtual process which can hint at new physics at high energy scales
- Was used to constrain Dirac monopoles to M > 120 GeV (PLB 262, 463 (1991)) – no recent study to my knowledge
- Large model uncertainties on such bounds
  - Higher-order corrections in perturbative calculations
  - Assume spin-1/2, point-like monopole
- Still, the authors claim to be able to provide correct order of magnitude

Z decay to three photons



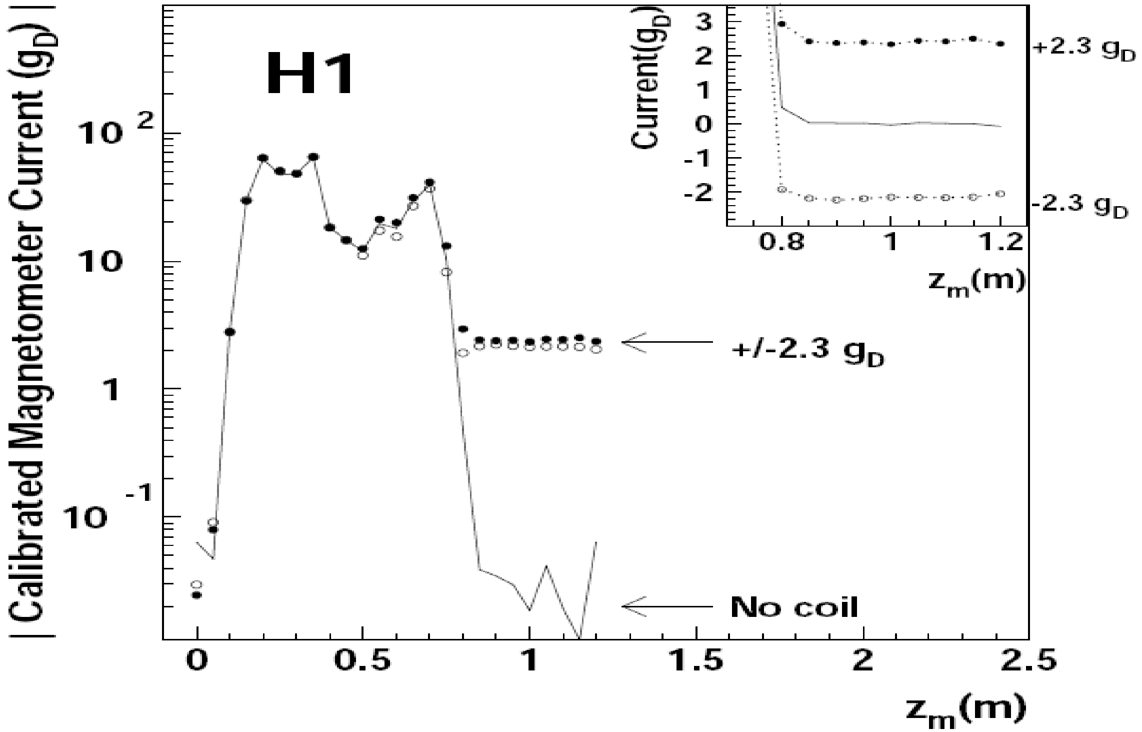


TLEP would be awesome!

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 $g \geq g_D$)

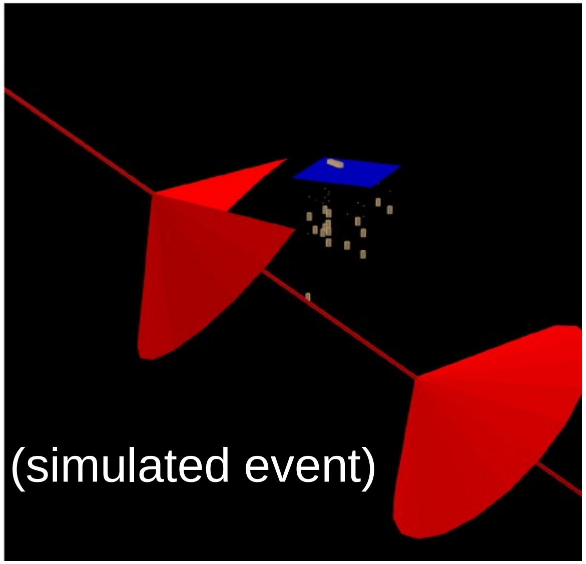
arXiv:hep-ex/0501039 (2005)

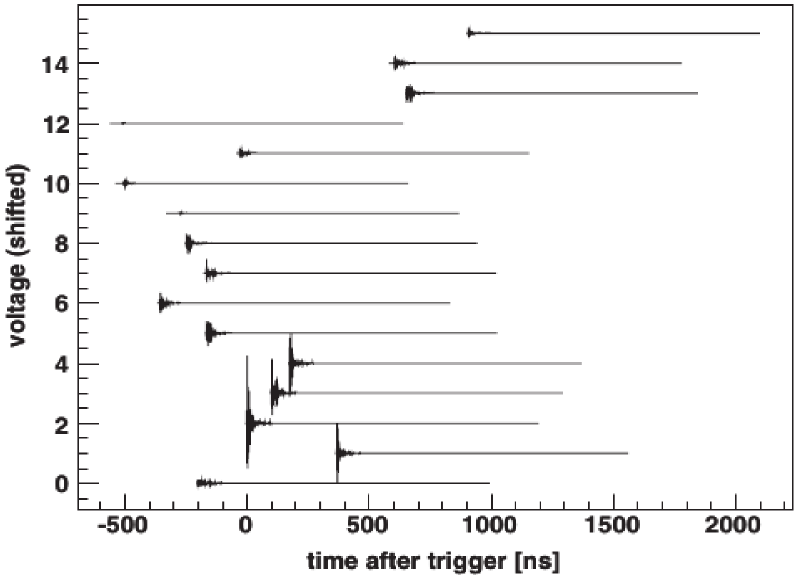


RICE (radio Cherenkov)

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

arXiv:0806.2129 (2008)





Magnetometer tests for trapped monopoles searches (1)

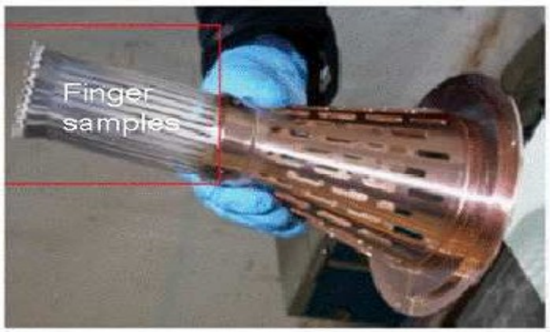
Laboratory of Natural Magnetism, ETH Zurich

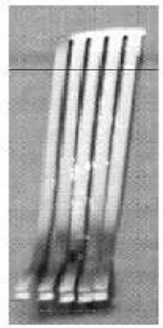
Magnetically shielded room

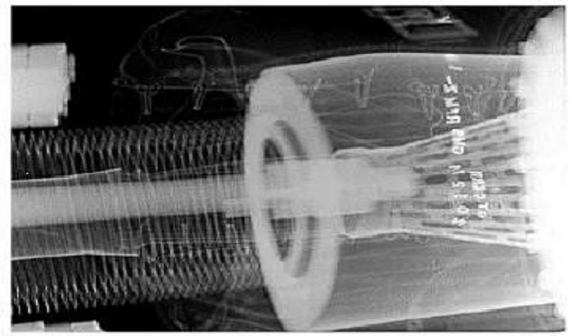
DC-SQUID magnetometer

Magnetometer tests for trapped monopoles searches (2)

Proof-of-principle using accelerator material near CMS

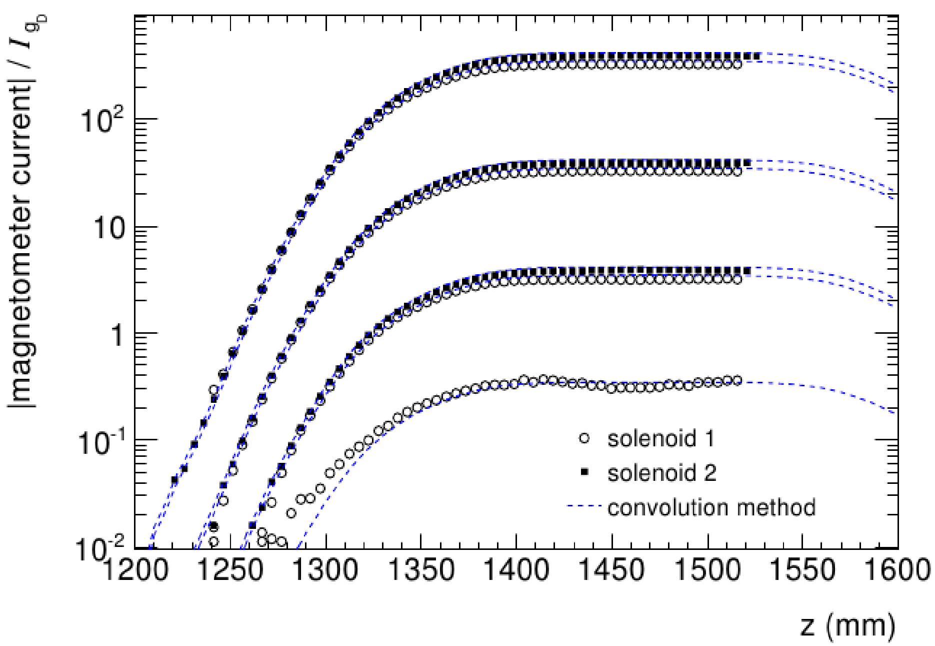




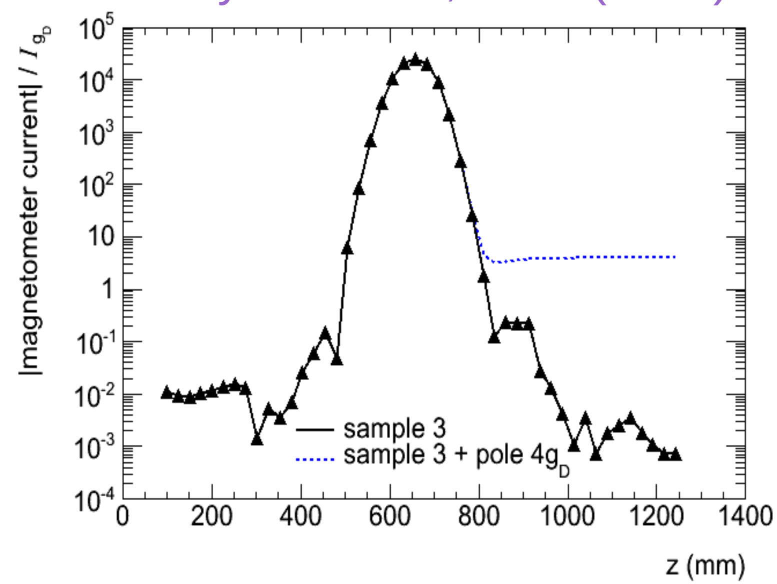


X-ray image of defective plug-in module

Calibration cross-check with long, thin solenoids



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



Iron ore (induction)

Superconducting coil placed under a furnace where iron ore Is heated to 1300 °C

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

Must also assume no binding to nuclei!

PRD 36, 3359 (1987)