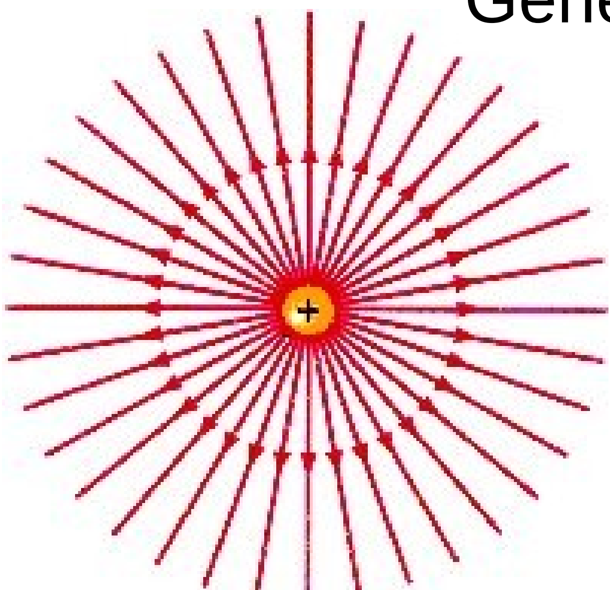
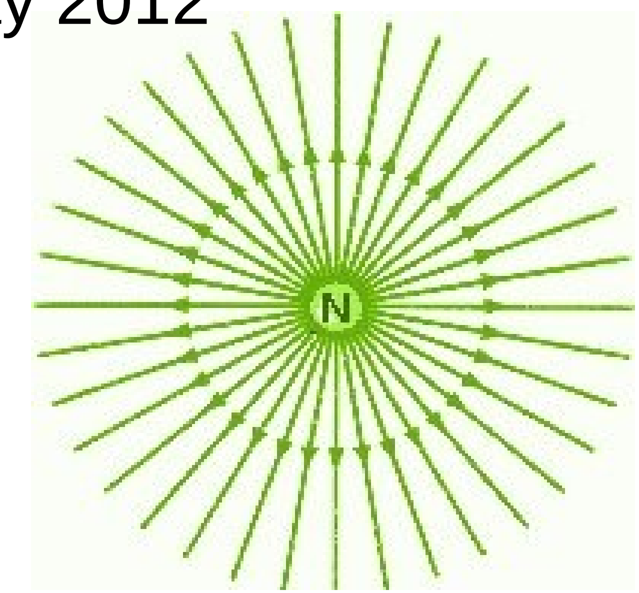
The search for the magnetic monopole

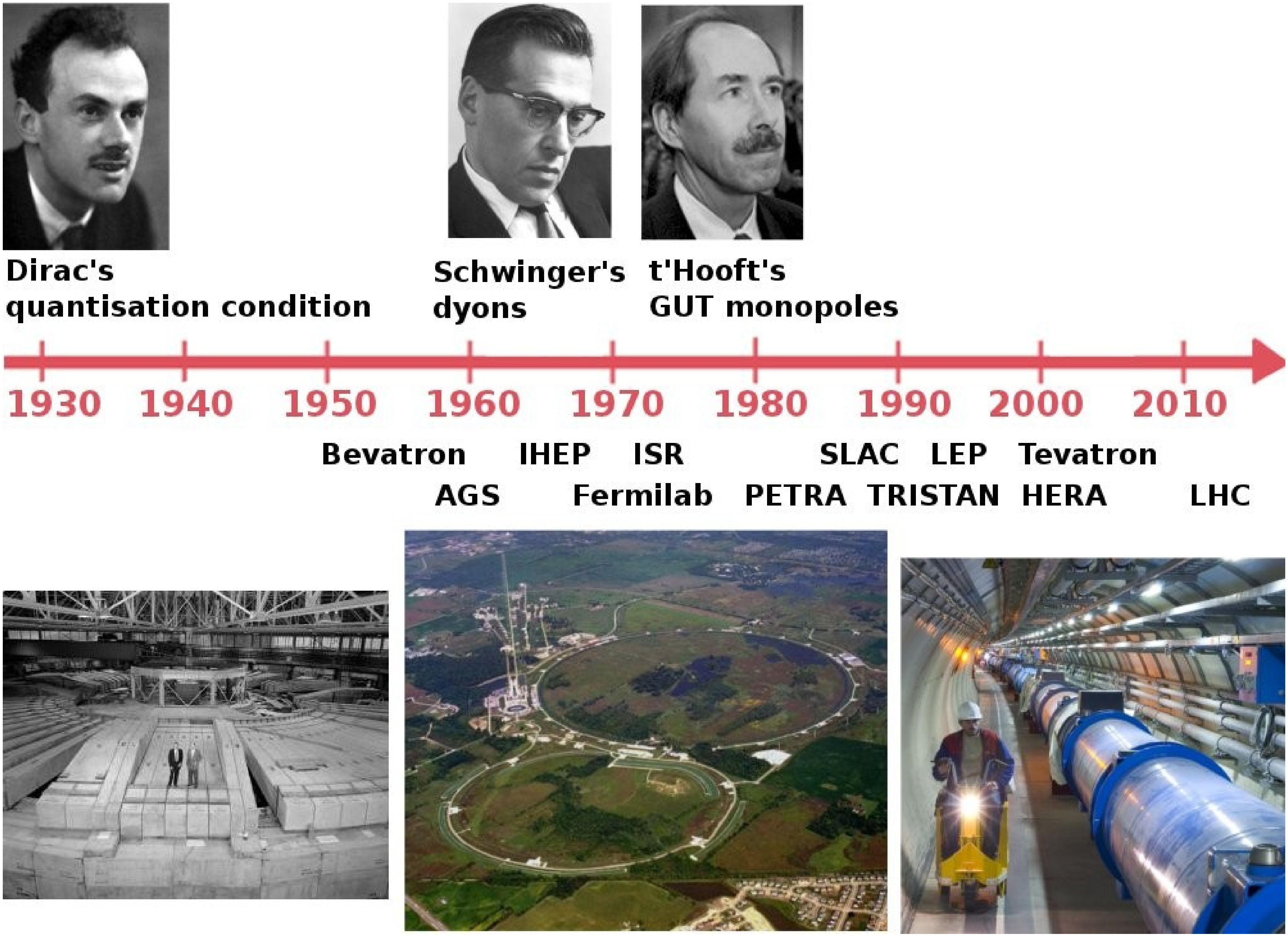
Philippe Mermod (University of Geneva)
Particle Physics Seminar
Geneva, 9 May 2012



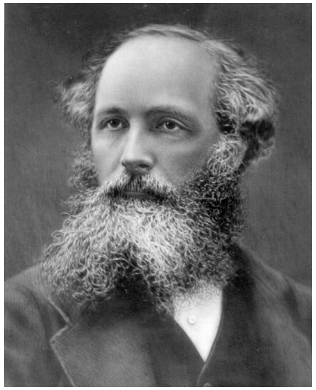


$$\nabla \cdot \overrightarrow{E} = 4\pi\rho_e$$

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

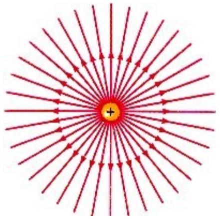

Dirac's
quantisation condition
Schwinger's
dyons
t'Hooft's
GUT monopoles
1930
1940
1950
1960
1970
1980
1990
2000
2010
Bevatron
IHEP
ISR
SLAC
LEP
Tevatron
AGS
Fermilab
PETRA
TRISTAN
HERA
LHC

Maxwell's equations (1862)



Without monopoles

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



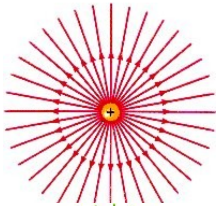
$$\nabla \cdot \mathbf{B} = 0$$

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

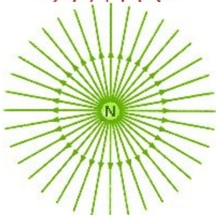
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

With monopoles

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



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

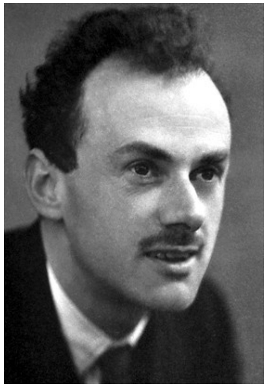


$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j_m}$$

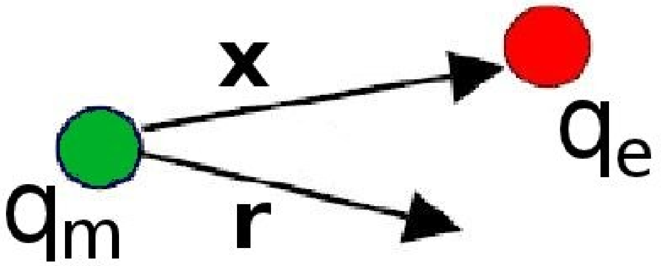
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

Dirac's argument

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



- Field angular momentum of electron-monopole system is quantised:



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

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

- Explains quantisation of electric charge!
  - Fundamental magnetic charge (n=1):

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

Schwinger's argument

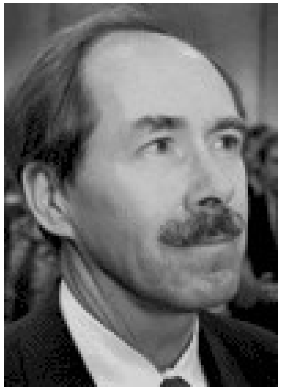
Phys. Rev. 144, 1087 (1966)

- 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 $|q_e|$=1/3*e* (down quark) as the fundamental electric charge, it even becomes $6g_D$

't Hooft and Polyakov's argument



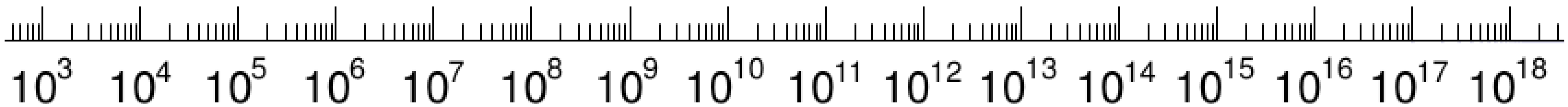
Nucl. Phys. B79, 276 (1974)

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

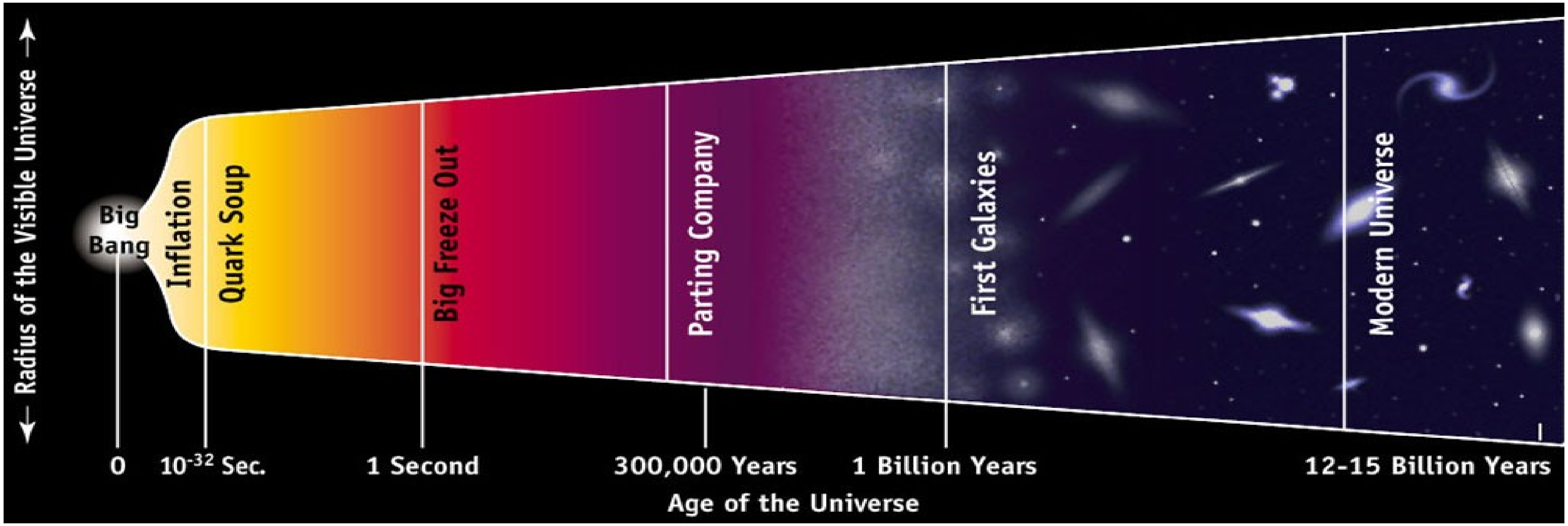


Possible monopole mass rage (GeV)

Primordial Monopoles

Big Catastrophe: standard cosmology predicts way too many monopoles!

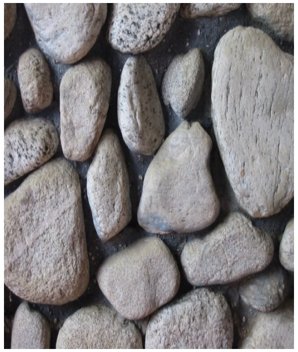
- Inflation theory can solve this problem
- Huge uncertainty on relic monopole abundances



Primordial "cosmic" monopole:

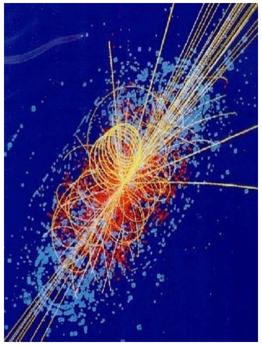
- Moving freely through outer space
- Accelerated to relativistic speeds by galactic magnetic fields if m < 10^{15} GeV
- Abundances uncertain

Primordial "stellar" monopole:



- Bound in matter before star formation
- Concentration uncertain, can be inhomogeneous today

Secondary monopole:



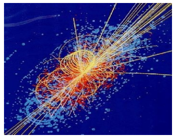
- Atmospheric production from high-energy cosmic ray
- Laboratory production in high-energy collisions at accelerators
- Cross section uncertain, presumably large

Experiments: where to search for monopoles?

- In flight (cosmic and atmospheric)

  - Limitation: detector size and time of exposure
- In bulk matter (stellar, cosmic and atmospheric)

  - Limitation: amount of material
- At accelerators (laboratory production)



  - Limitation: center-of-mass energy

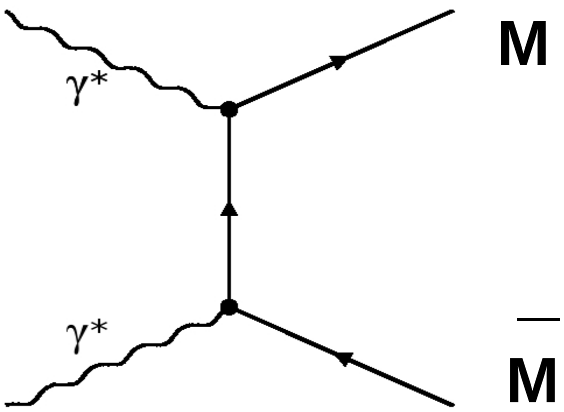
Property: production

EM coupling constant for Dirac charge = 34.25

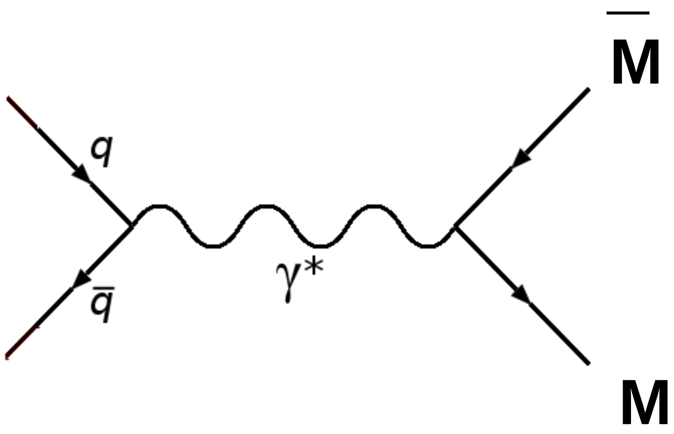
→ non-perturbative dynamics, no reliable cross sections and kinematics!

<u>"Natural" benchmark models:</u>

photon fusion



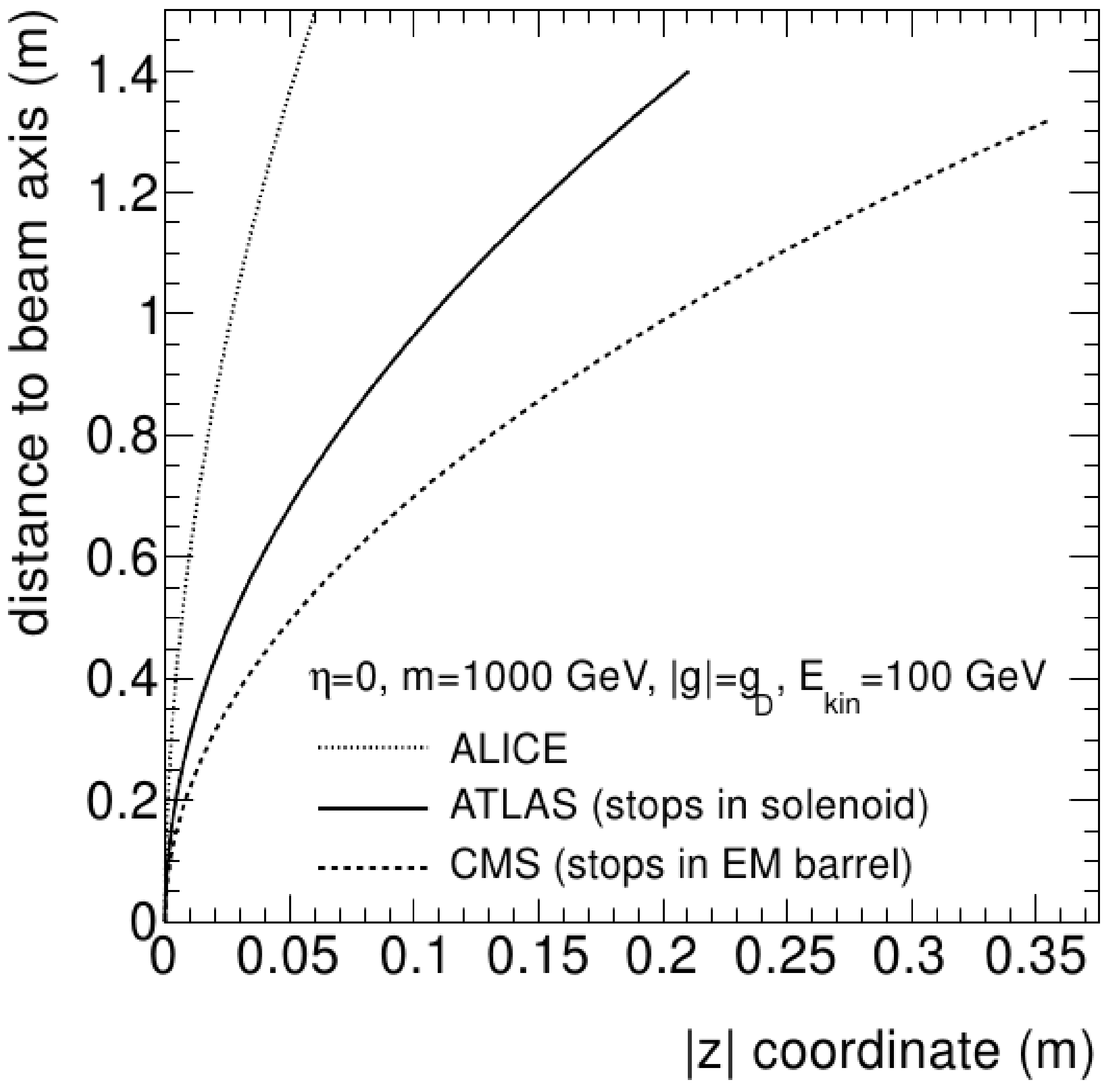
Drell-Yan



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

Property: bending

arXiv:1112.2999



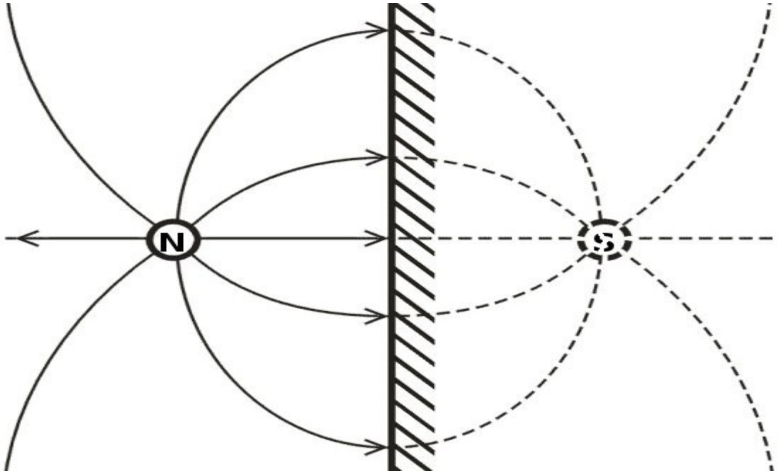
Acceleration along magnetic field:

$$F_m = q_m \cdot B$$

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

Property: binding in matter

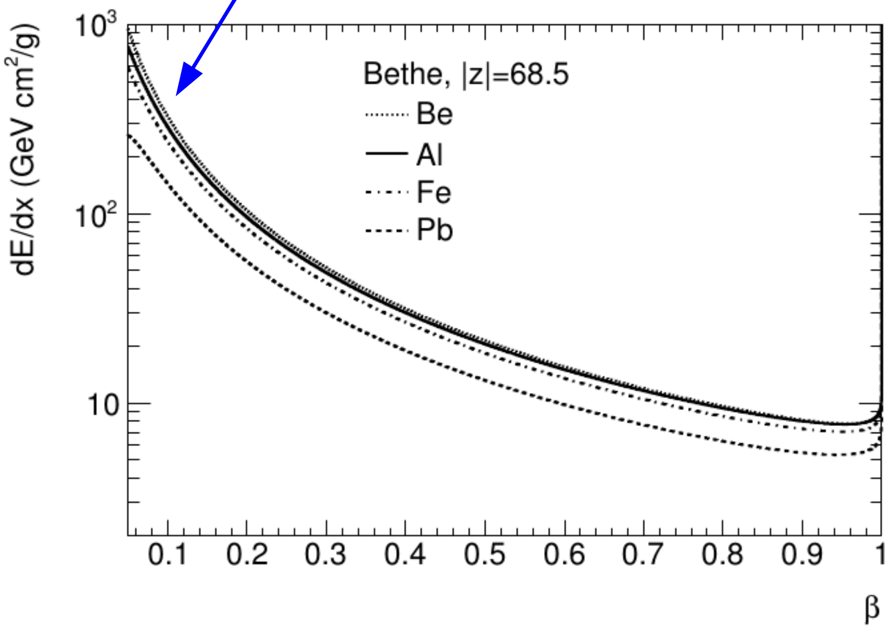
- **To atoms**
  - Binding energies of the order of a few eV
- **To nuclei with non-zero magnetic moments**
  - Binding energies of the order of 200 keV
- **At the surface of a ferromagnetic**
  - Image force of the order of 10 eV/Å
  - **Robust prediction** (classical)



Property: ionisation energy loss

Electric

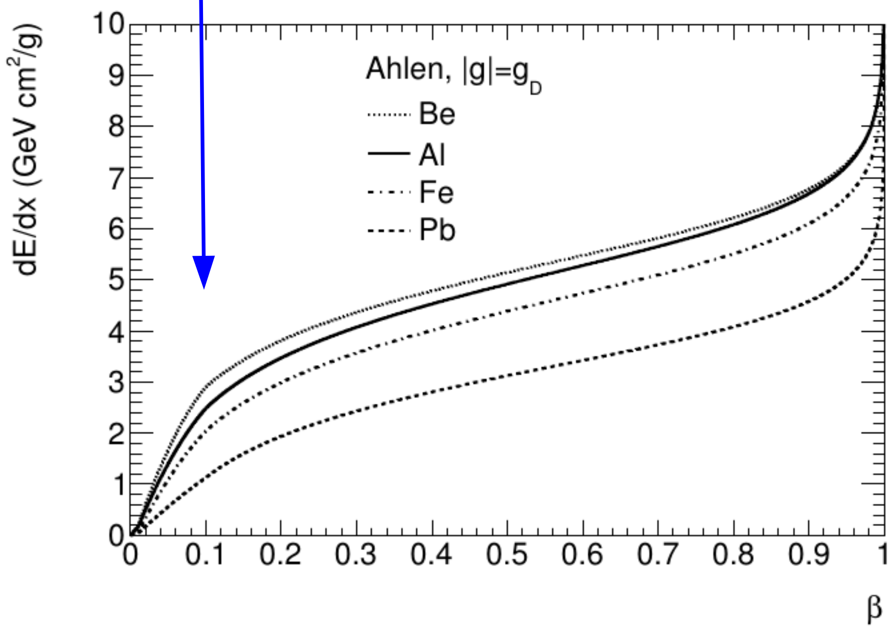
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2\right]$$



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!

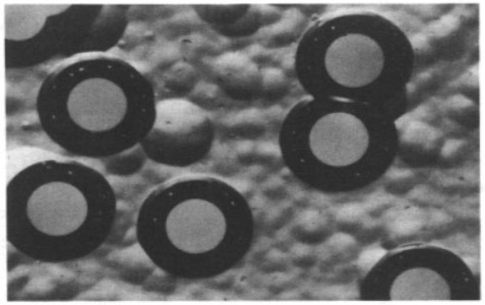


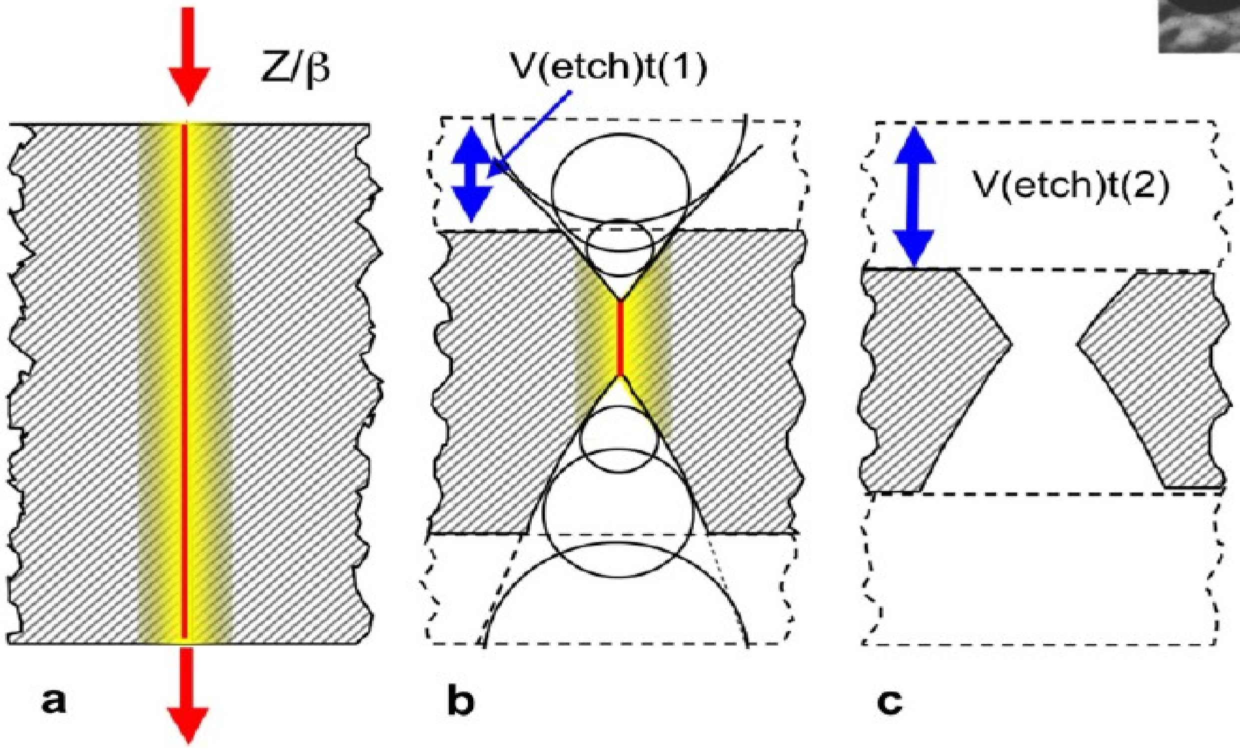
Dirac monopole: $|g_D| = 68.5$ → several thousand times greater d*E*/d*x* than a minimum-ionising |z|=1 particle

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

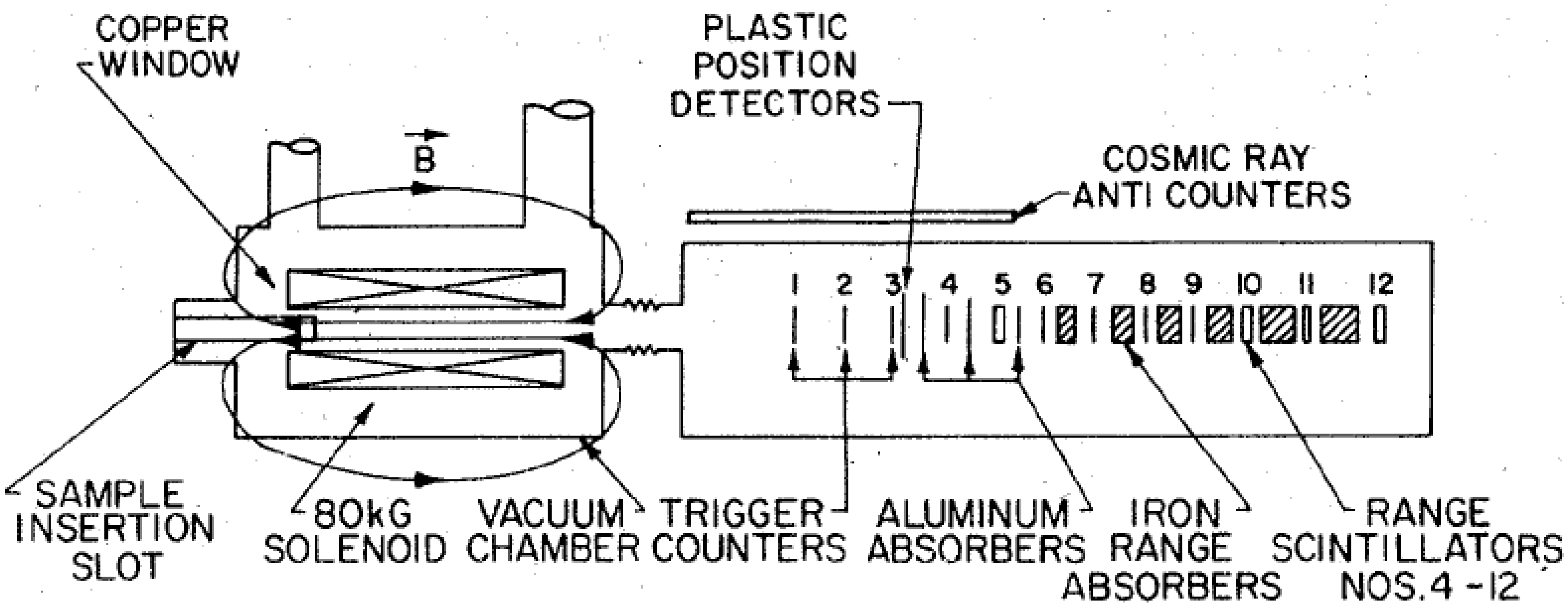




Detection: extraction technique

Principle: strong (> 50 kG) magnetic field applied to extract and accelerate monopoles trapped in matter

- Detector telescope measures d*E*/d*x* and range
- Limited mass and charge sensitivity

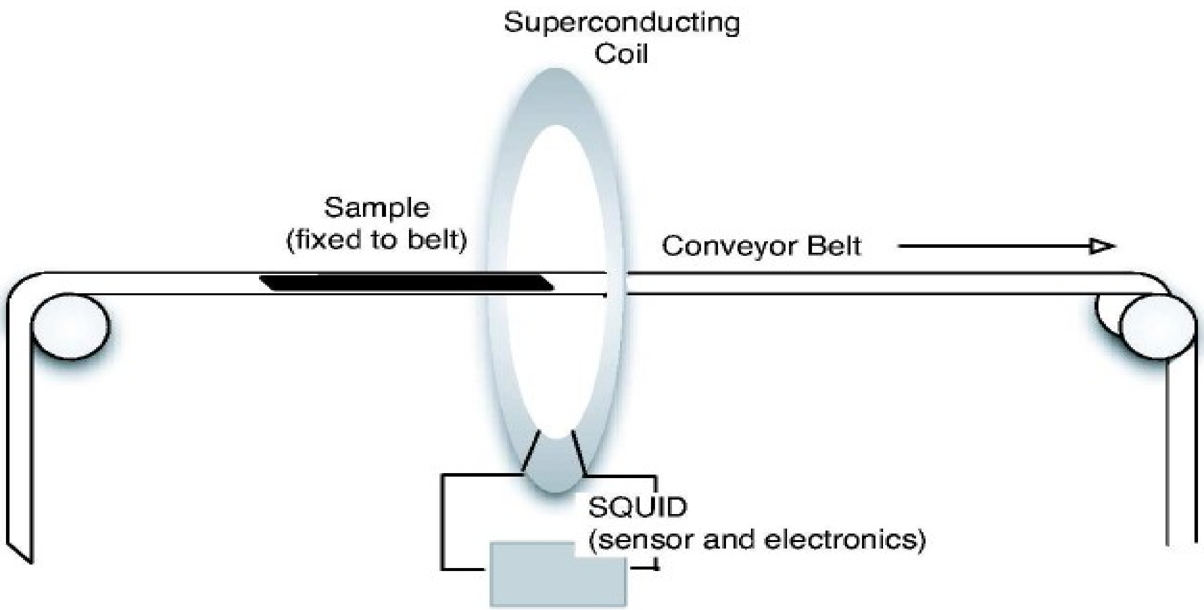


Detection: induction technique

Principle: moving magnetic charge induces electric field

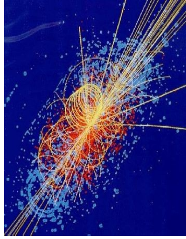
Tiny permanent current measured after passage of sample through superconducting coil

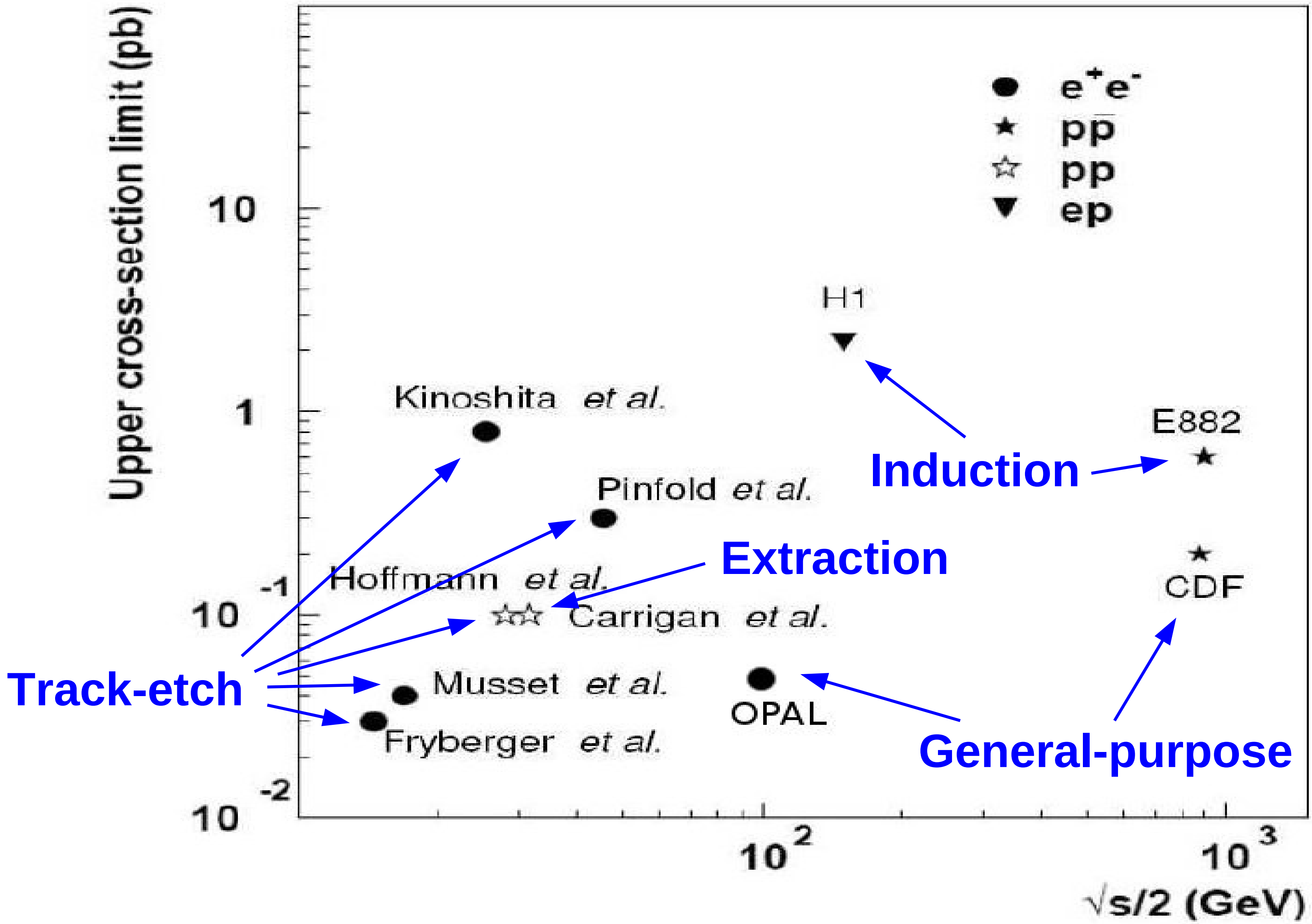
- Directly proportional to magnetic charge
- No mass dependence



Collider searches

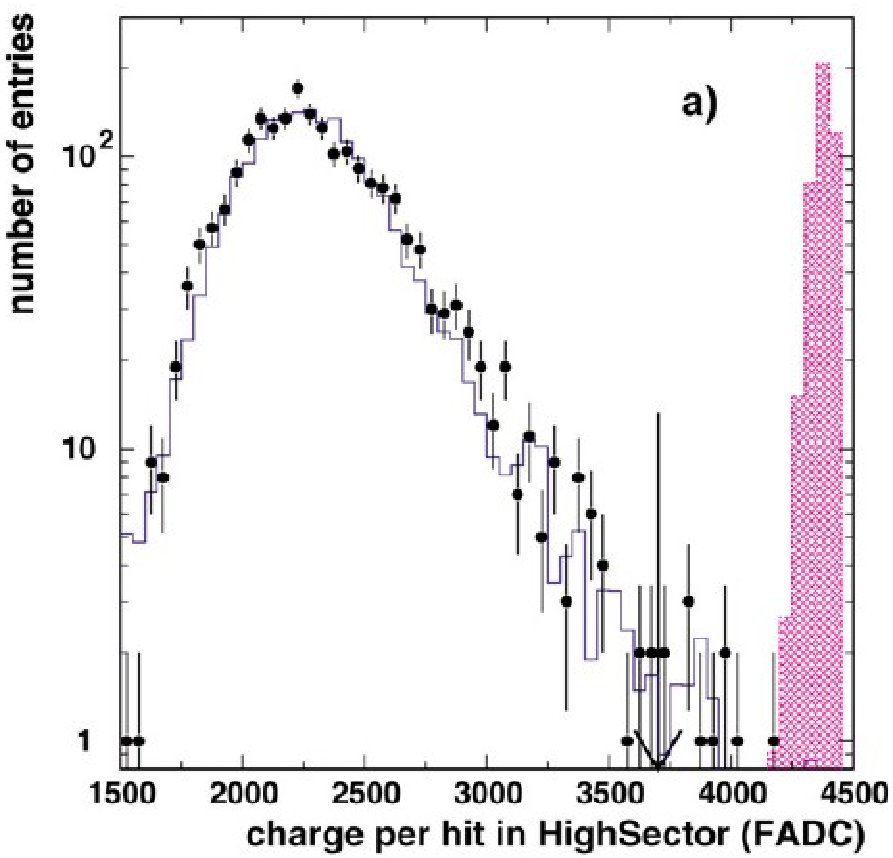
current cross section limits for a Dirac monopole:



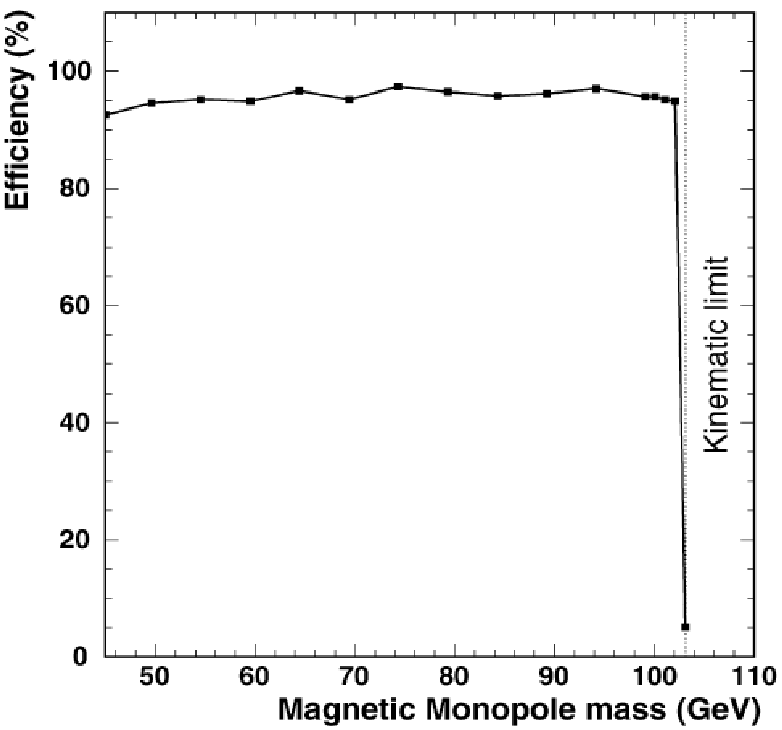


OPAL (LEP2)

- Special trigger requiring high thresholds in jet chamber
- Jet chamber also used offline for more refined selection
- 0.05 pb limit (45 to 102 GeV Dirac monopole)

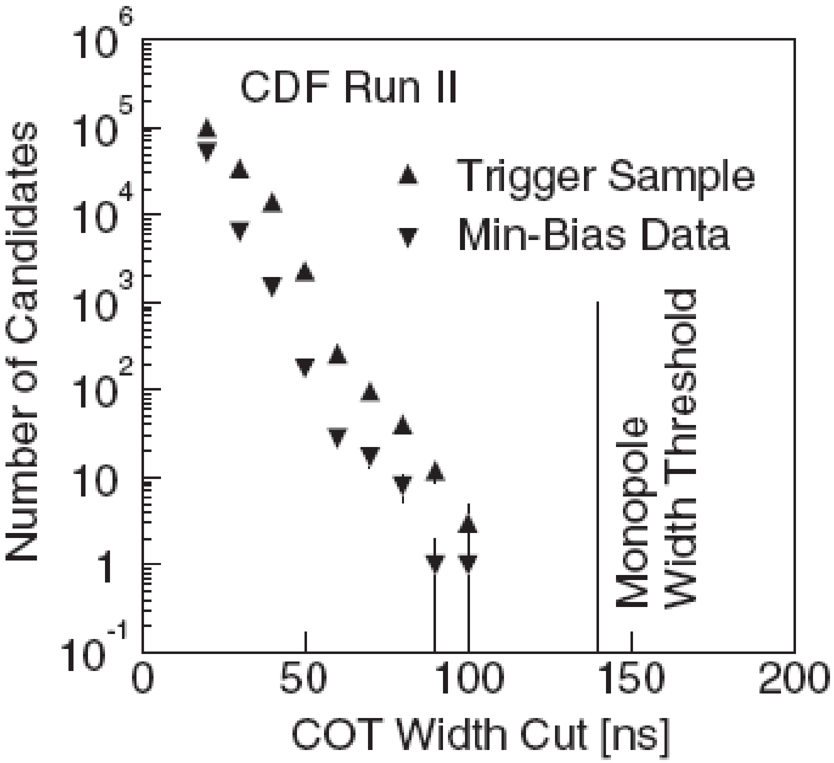


arXiv:0707.0404 (2008)

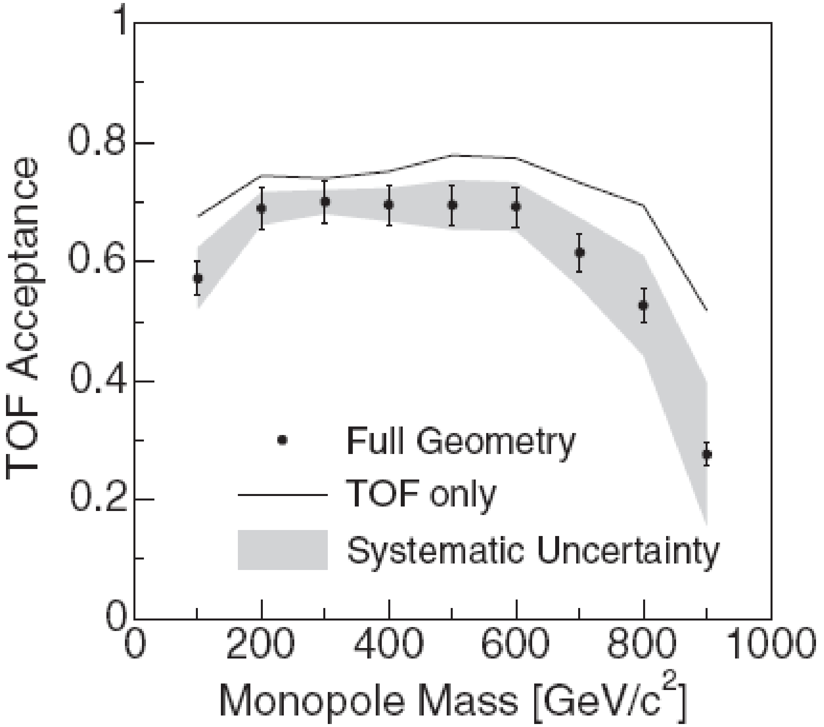


CDF (Tevatron)

- Special trigger requiring high pulse in TOF scintillator
- High-ionisation hits in tracker, straight line in *xy* plane
- 0.2 pb limit (200 to 700 GeV Dirac monopole)

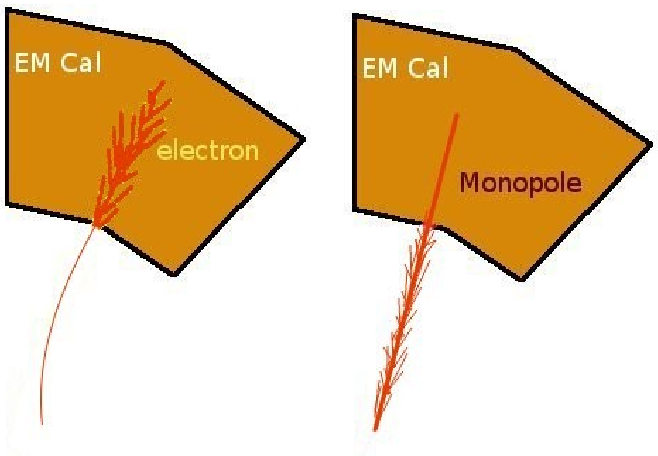


arXiv:hep-ex/0509015 (2006)



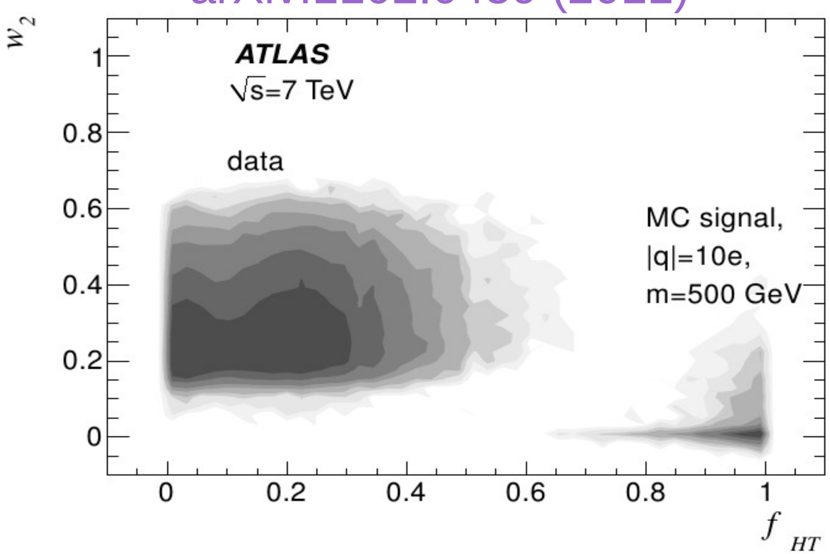
ATLAS and CMS (LHC)

- Need EM trigger
  - See only monopoles which reach EM calorimeter (high energy or low charge)



- Pioneering (Summer 2010) ATLAS search, using standard tracking
  - Interpretation for electric charge 6e < $|q_e|$ < 17e

arXiv:1102.0459 (2011)

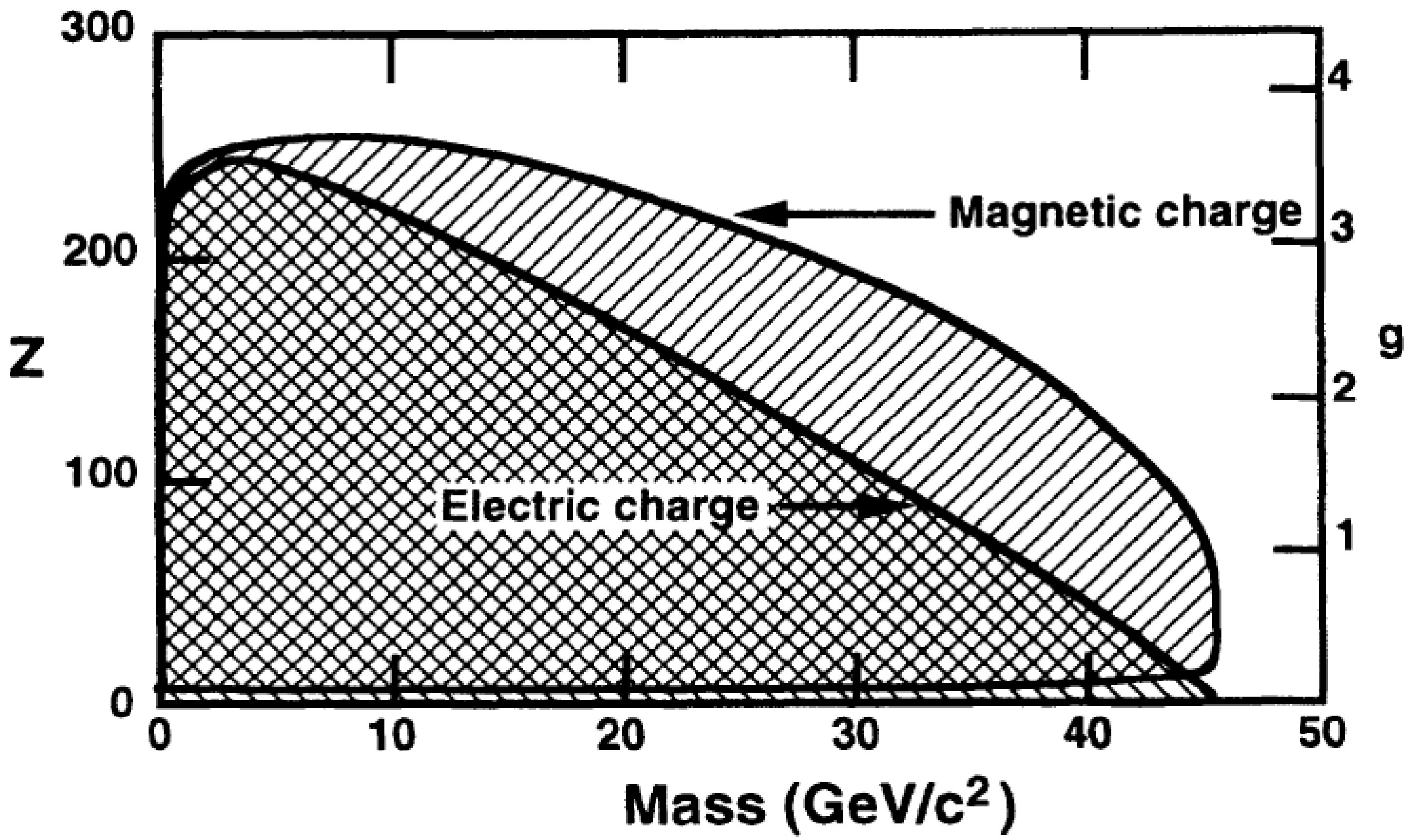


- Dedicated monopole searches underway
  → **first results coming very soon!**
- Dedicated triggers being designed

MODAL (LEP1, track-etch)

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

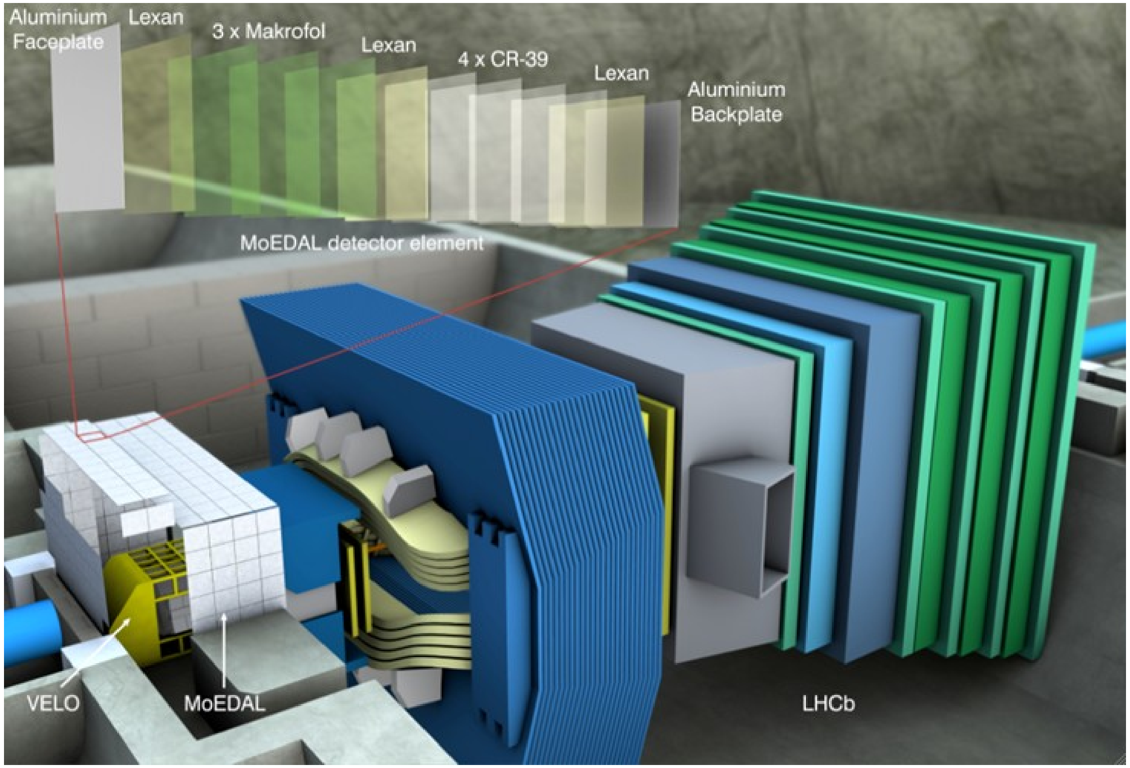
Phys. Rev. D 46, R881 (1992)



MoEDAL (LHC, track-etch)

The seventh LHC experiment, dedicated to highly ionising particle detection

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



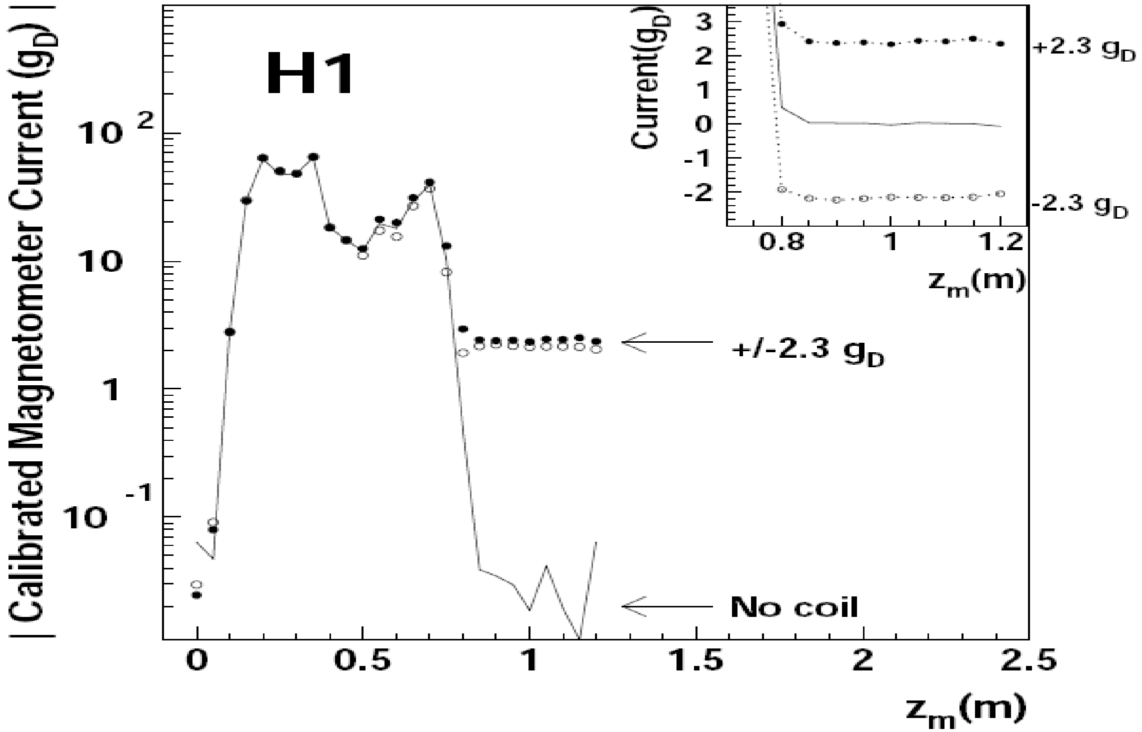
Test array already deployed around LHCb interaction point

Main run planned for 2014-2015

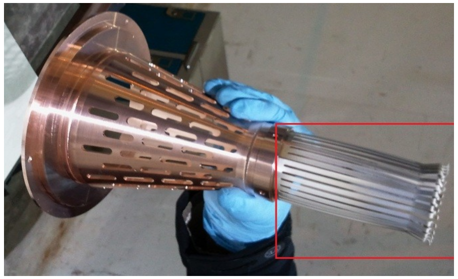
H1 beam pipe (HERA, induction)

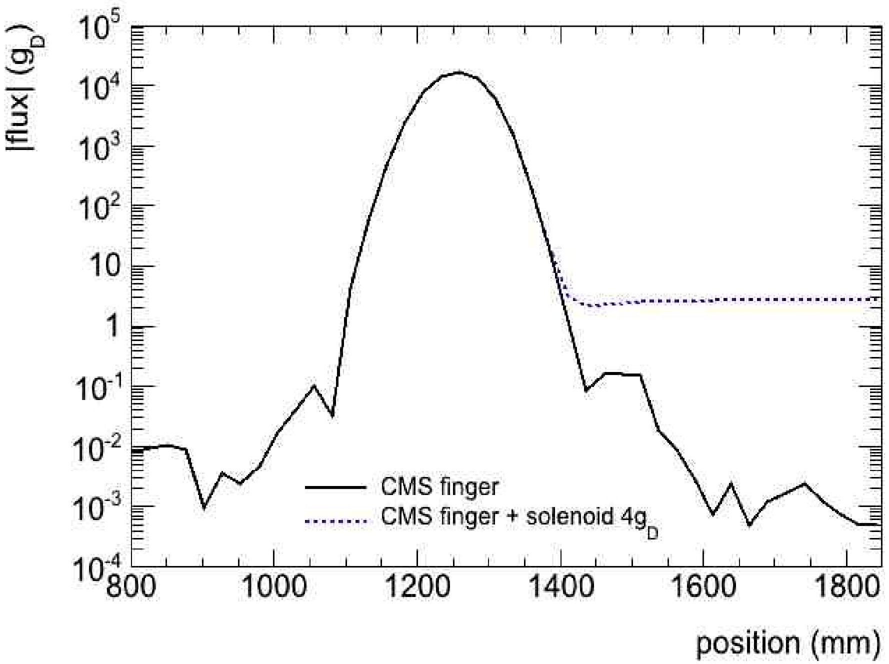
- Monopoles and dyons with very high magnetic charges would stop in the Al beam pipe!
- 0.1 – 1 pb limit (up to 140 GeV monopole with $g \geq g_D$)

arXiv:hep-ex/0501039 (2005)



CMS debris (LHC, induction)





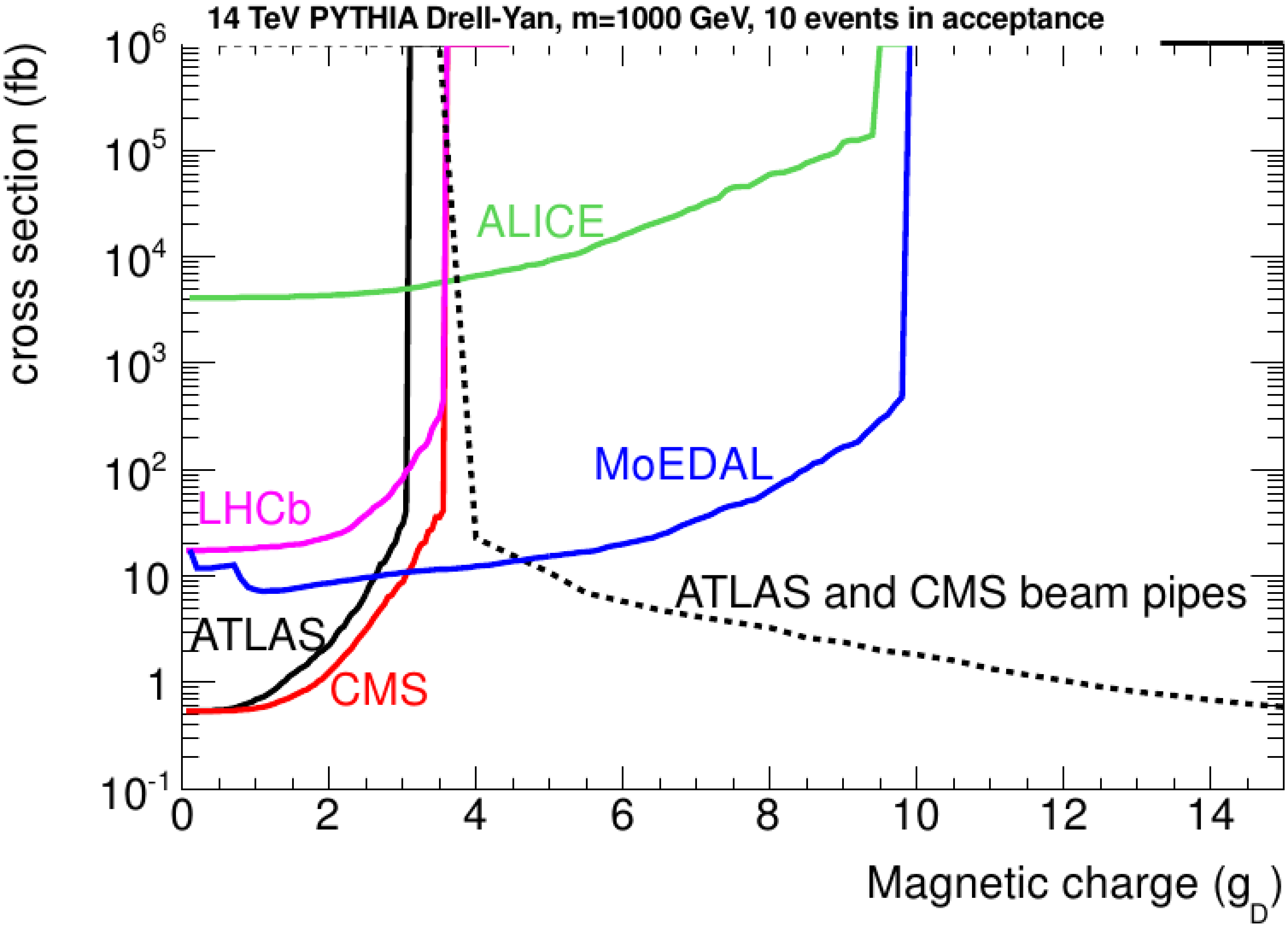
SQUID tests performed at Laboratory for Natural Magnetism (ETH Zürich)

- Using CMS fingers, in full view of interaction point

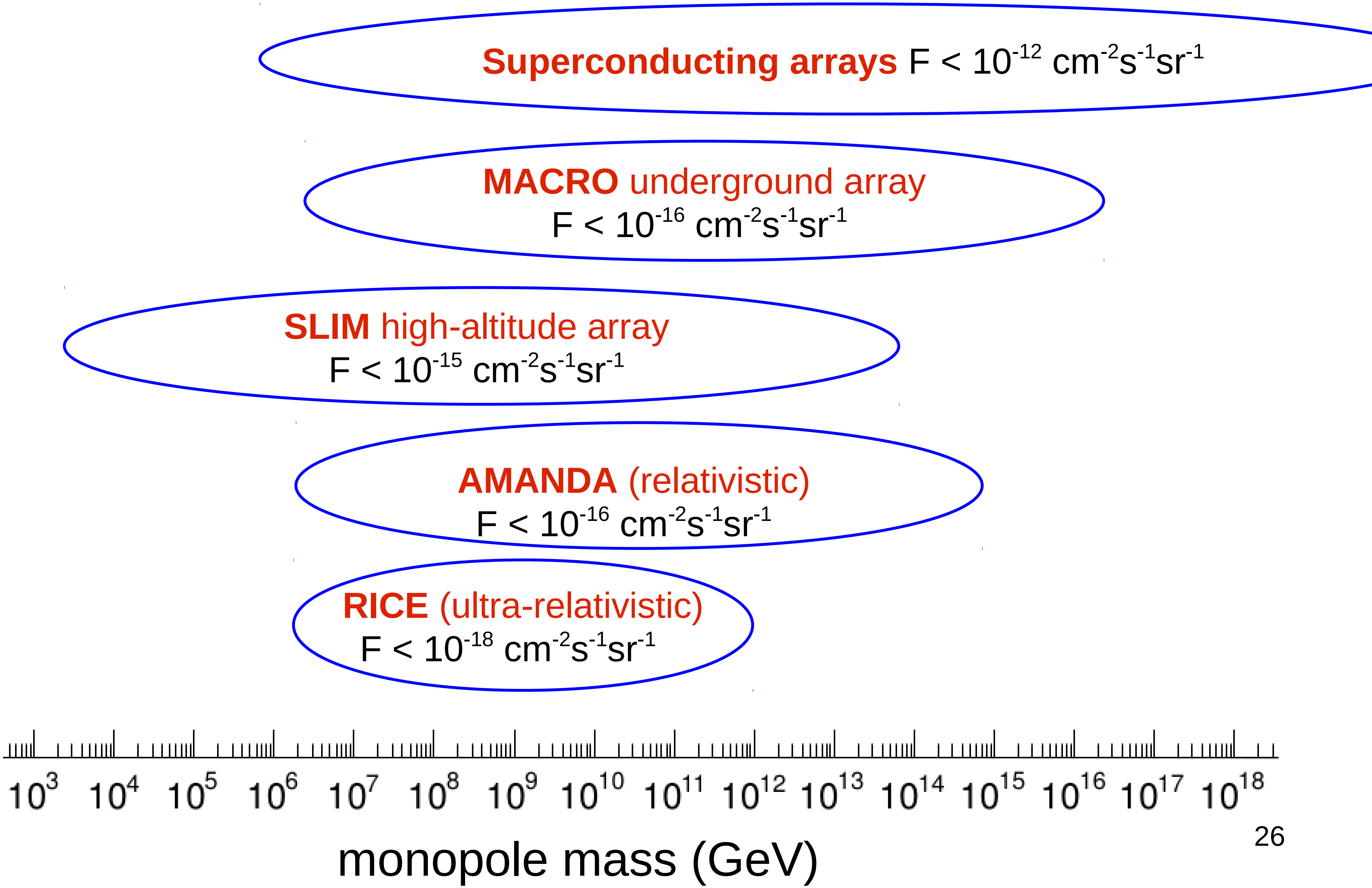
Proposal: **search for monopoles in ATLAS and CMS beam pipes** (to be replaced next year!)

Sensitivities of LHC experiments

arXiv:1112.2999 (2012)



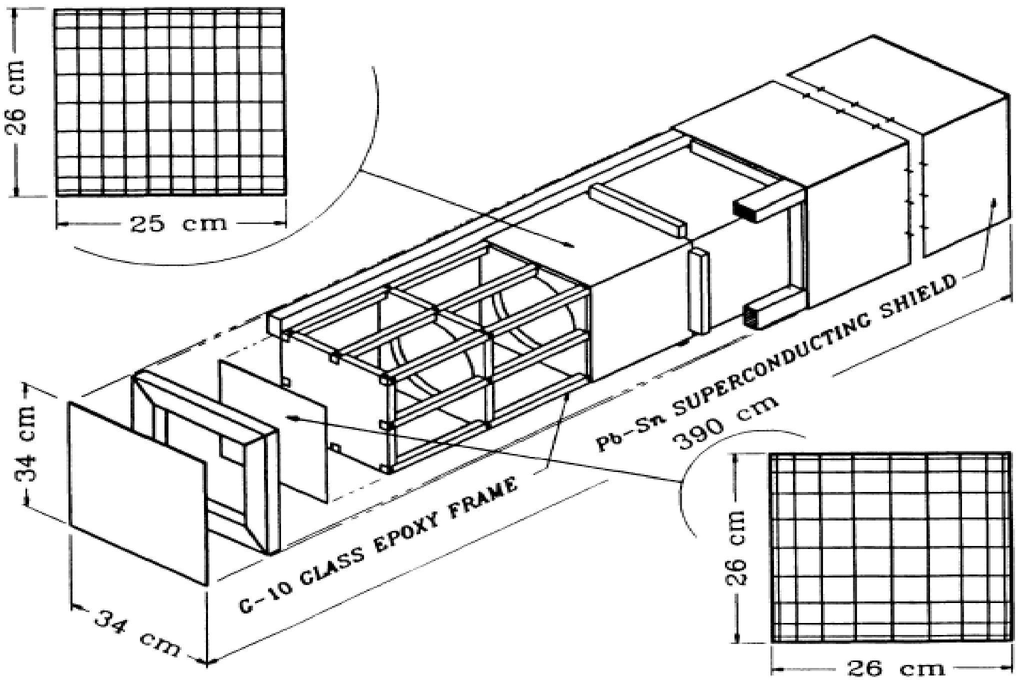
Cosmic ray searches



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)

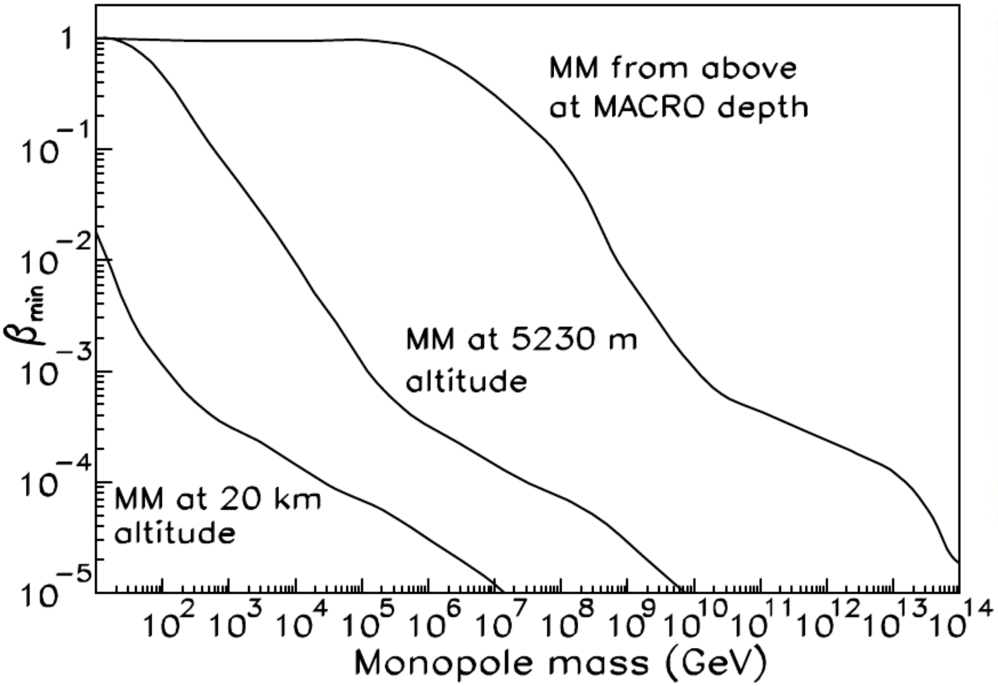
SLIM (track-etch)

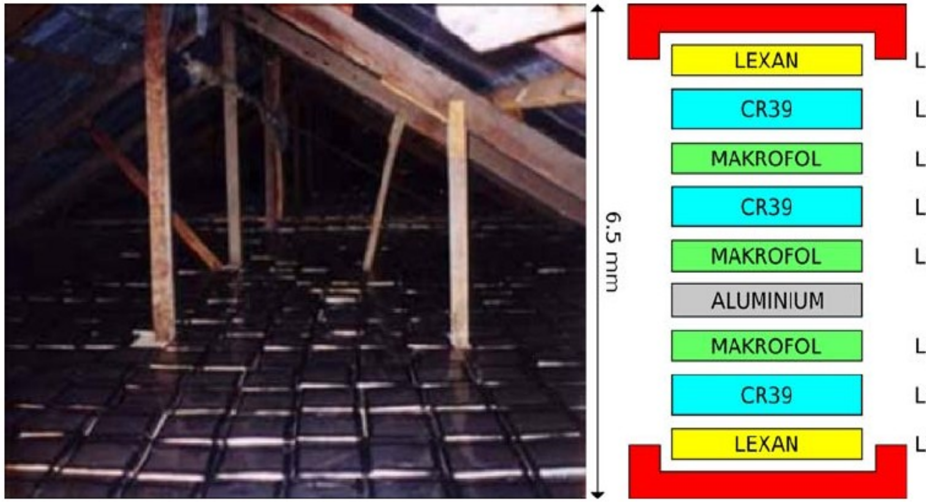
- Altitude: 5230 m

(Chacaltaya observatory)

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

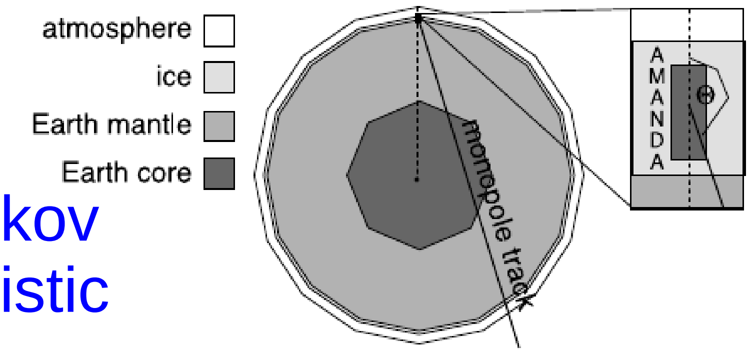
arXiv:0801.4913 (2008)





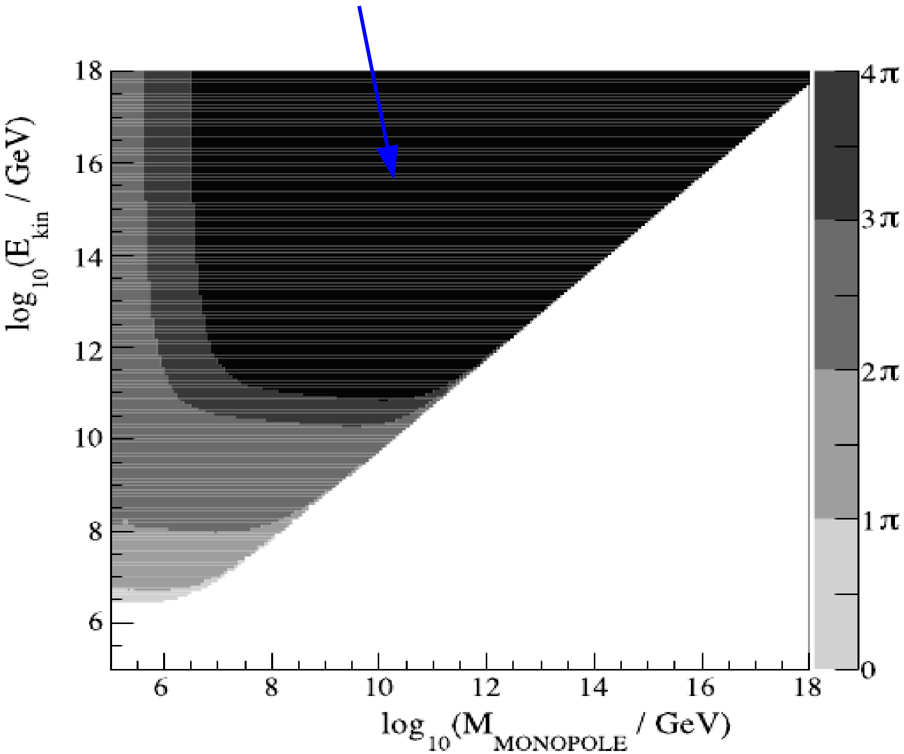
AMANDA-II (Cherenkov)

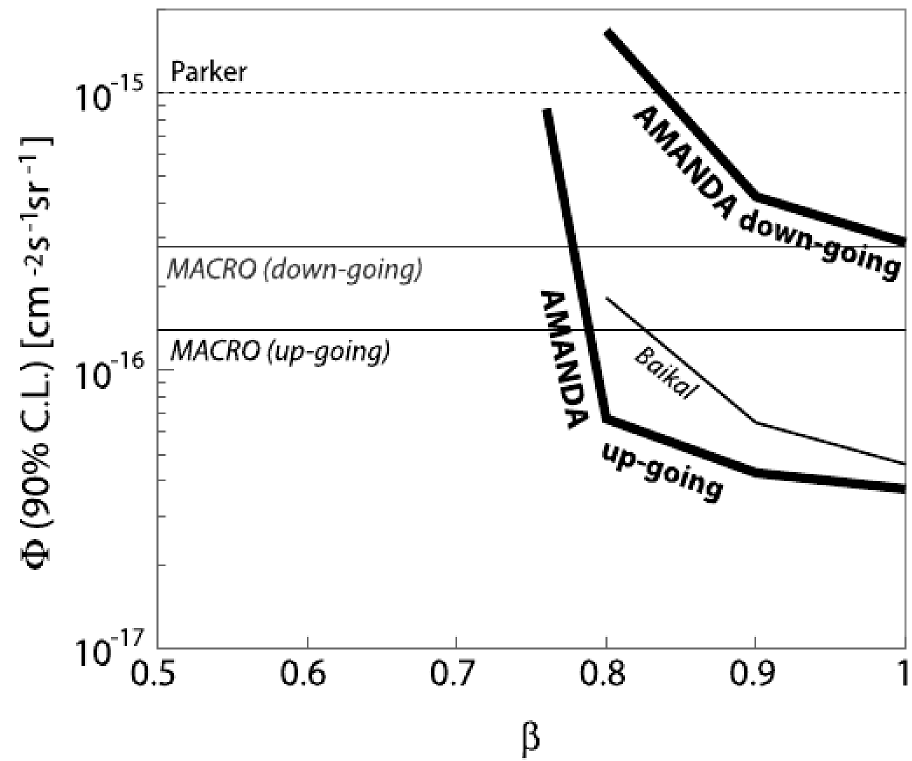
- PM arrays buried in polar ice
  - Can identify intense Cherenkov light expected from relativistic monopole ($\beta > 0.8$)



- Dark area: sensitive to up-going (much less backgrounds)

EPJC 69, 361 (2010)

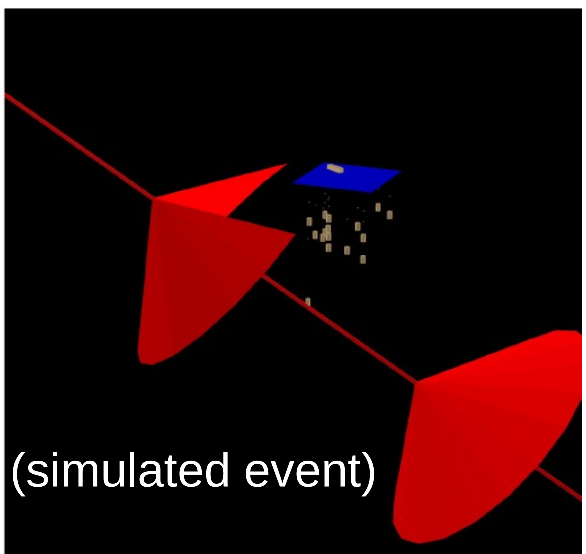


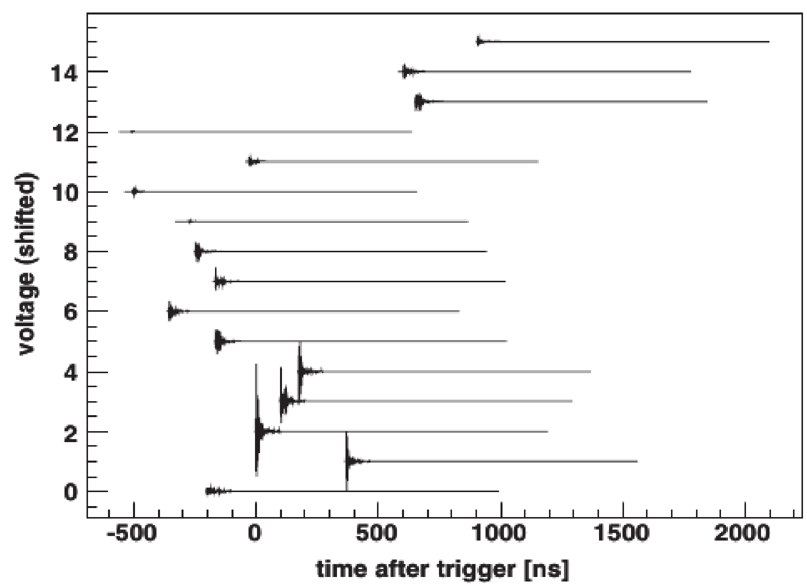


RICE (radio Cherenkov)

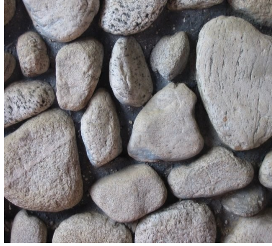
- Antennas buried in polar ice
  - Can identify strong radio wave signal from coherent Cherenkov radiation expected from ultra-relativistic monopole ($\beta \approx 1$)
    → "intermediate mass"
- F < 10^{-18} cm^{-2}s^{-1}sr^{-1} ($\gamma > 10^{7}$)

arXiv:0806.2129 (2008)


(simulated event)



Bulk matter searches



Seawater, air, sediments (cosmic)
$\rho < 2\cdot10^{-29}$ mon./nucleon

Rocks (cosmic)
$\rho < 5\cdot10^{-30}$ mon./nucleon

Moon rocks (cosmic)
$\rho < 3\cdot10^{-28}$ mon./nucleon

Meteorites (stellar)
$\rho < 3\cdot10^{-29}$ mon./nucleon

Polar volcanic rocks (stellar)
Potentially probe $< 10^{-29}$ mon./nucleon

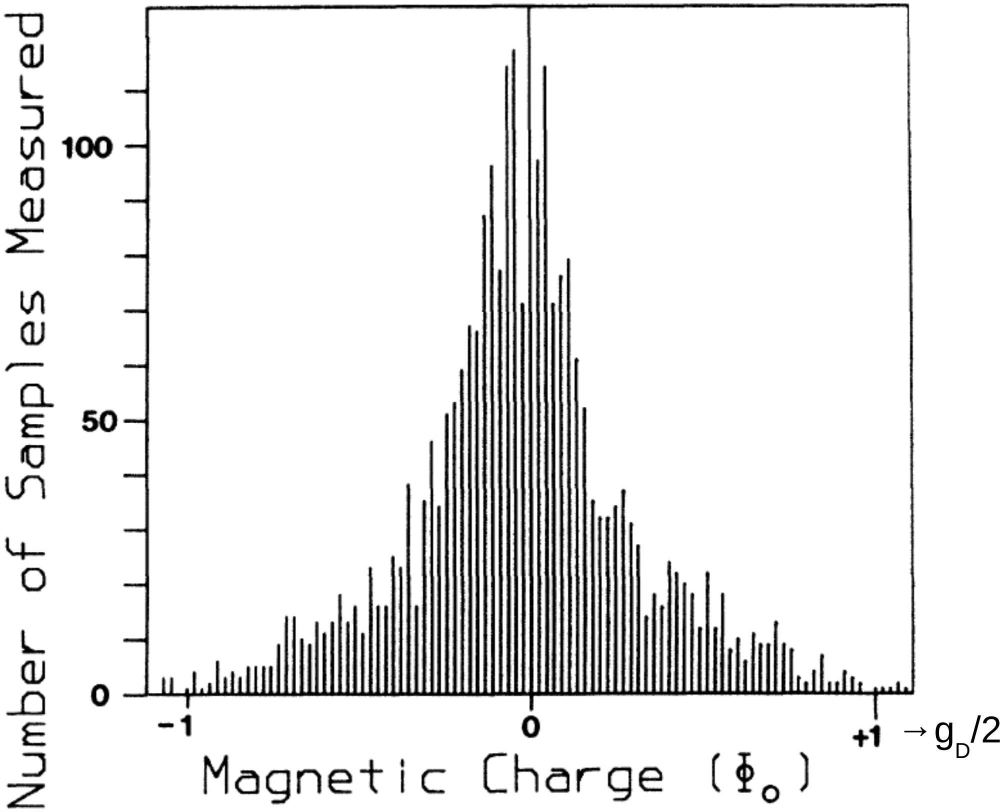
10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18}

monopole mass (GeV)

Deeply buried rocks and seawater
(induction – cosmic)

PRA 33, 1183 (1986)

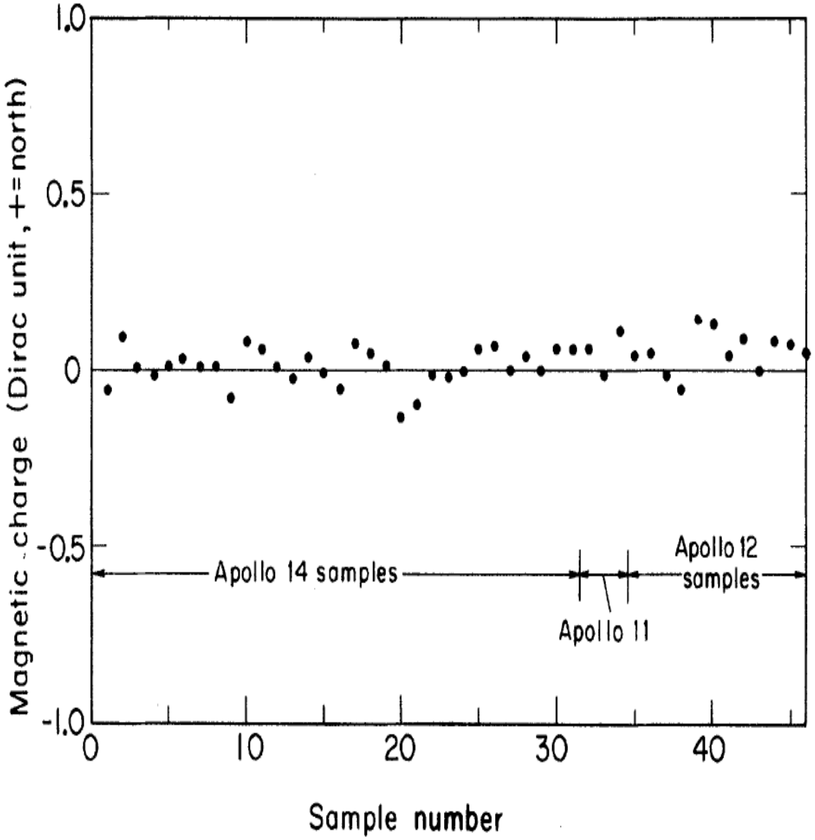
- Hundreds of kilograms of material analysed with large superconducting detector
- Depths of up to 25 km → stop higher-energy monopoles
- $\rho < 5 \cdot 10^{-30}$ mon./nucleon

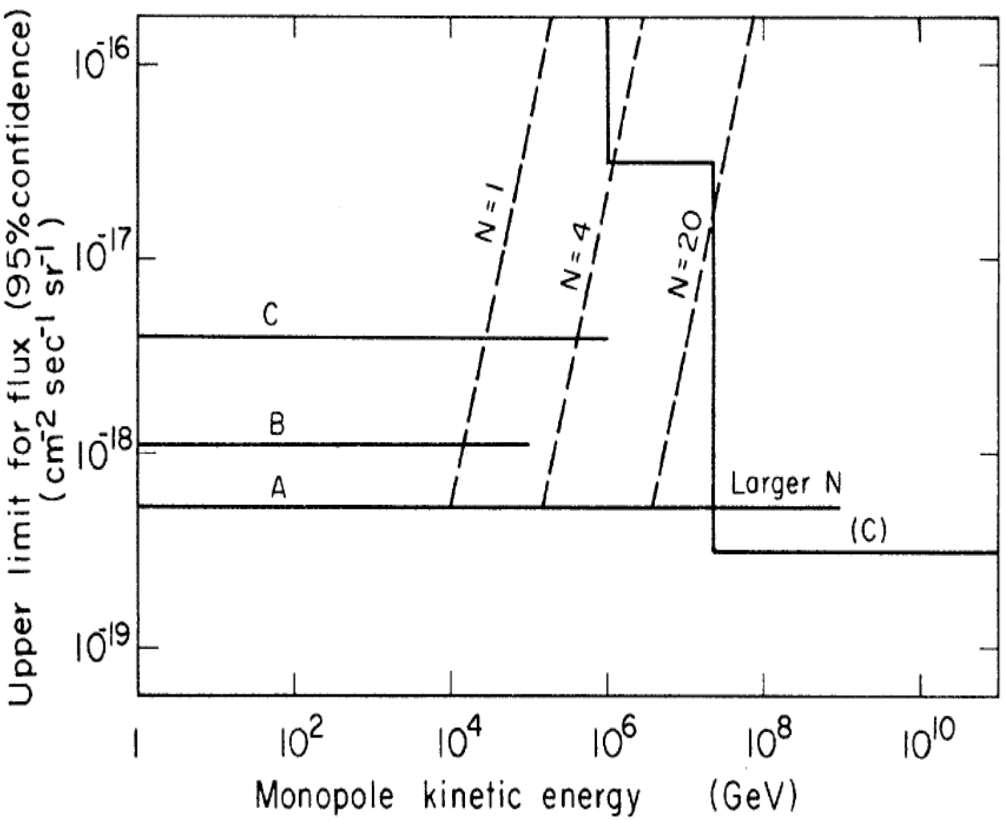


Moon rocks (induction – cosmic)

- Exposure: 4 billion 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)





Meteorites (induction – stellar)

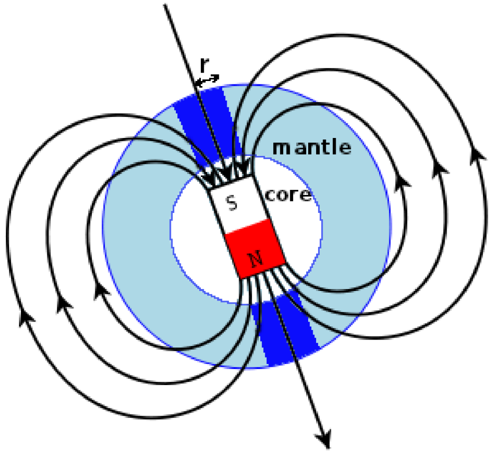
- **Stellar monopoles** heavier than the heaviest nuclei
  - ➔ Sank to the Earth's interior during Earth's formation
  - ➔ Crust depleted today
- Motivates searching in meteorites, assuming:
  - – Impact did not dislodge monopole
  - – Meteoroid does not originate from planetary crust
- 112 kg of meteorites analysed
- $\rho < 3 \cdot 10^{-29}$ mon./nucleon PRL 75, 1443 (1995)

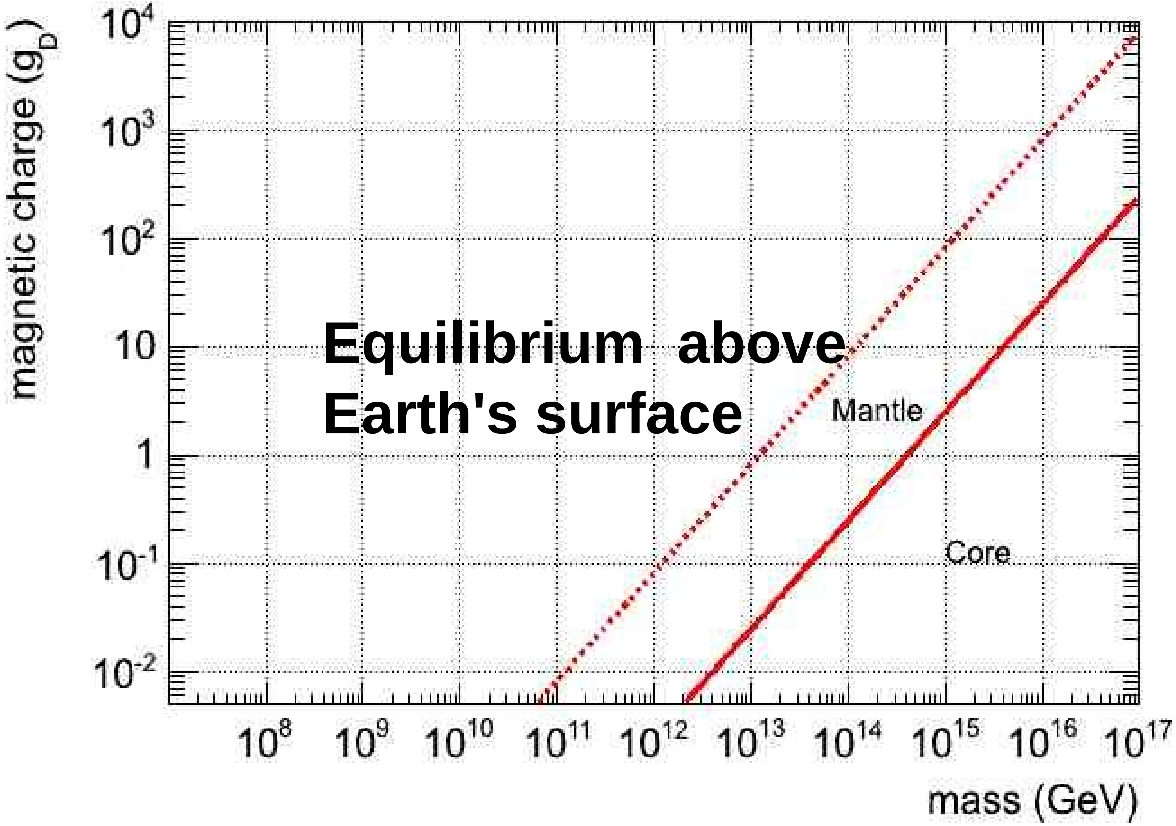
Possible future search: comets

→ Contain materials that the solar system formed from

Polar volcanic rock project (induction – stellar)

- **Stellar monopoles inside Earth** would migrate along the Earth's magnetic field
  - Position with all forces in equilibrium
  - May be found in polar volcanoes!





3 kg of samples from Antarctica ready to be analysed

Summary

- Magnetic monopoles are fundamental, well-motivated objects
  - Their non-existence would be a mystery
- Extensive searches at accelerators, in cosmic rays in in matter constrain the monopole masses, fluxes and abundances
  - Might still be there, beyond the reach of past experiments
- Future searches need to be done in a larger scale than before, or in unusual places
  - In returned comet samples
  - In polar volcanic rocks
  - Around LHC interaction points...

1ST MOEDAL PHYSICS WORKSHOP & COLLABORATION MEETING

JUNE 20TH (OPEN WORKSHOP IN THE CERN GLOBE)
JUNE 21ST (COLLABORATION MEETING IN SALLE DIRAC)

WELCOME

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Extra slides

Monopoles are accelerated along magnetic fields, draining their energy

- If monopoles were very abundant, all magnetic dipoles would be neutralised
- Galactic magnetic field is not depleted → **constrains the cosmic monopole flux** (Parker limit):

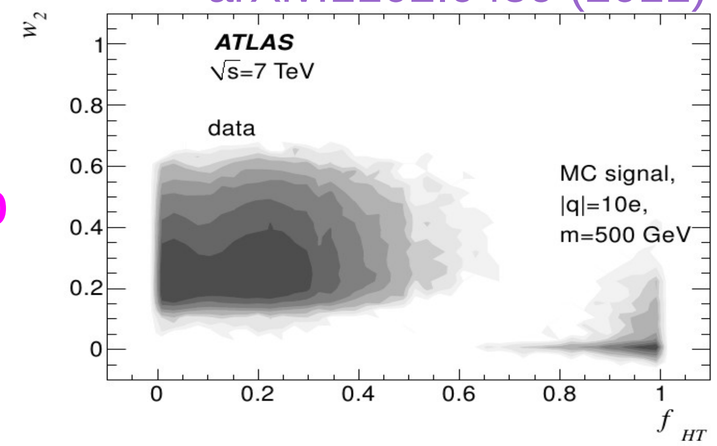
$$F < 10^{-15}\ \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

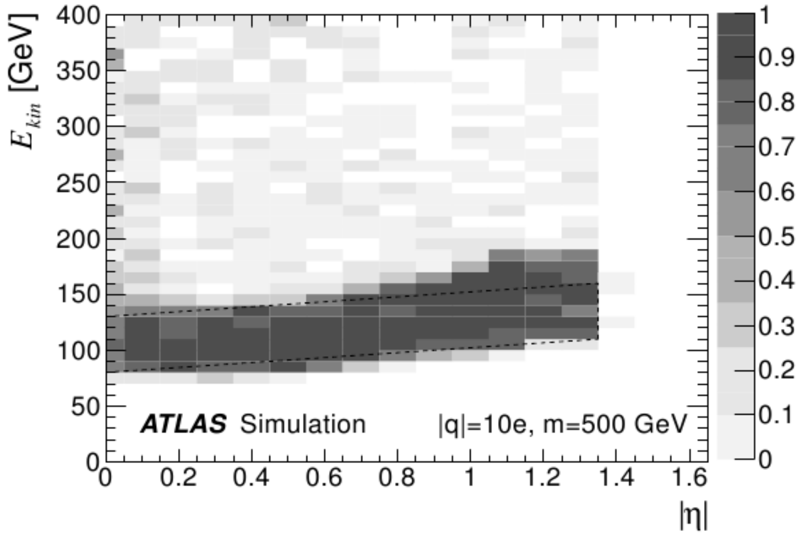
ATLAS search multiply-charged particles

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)

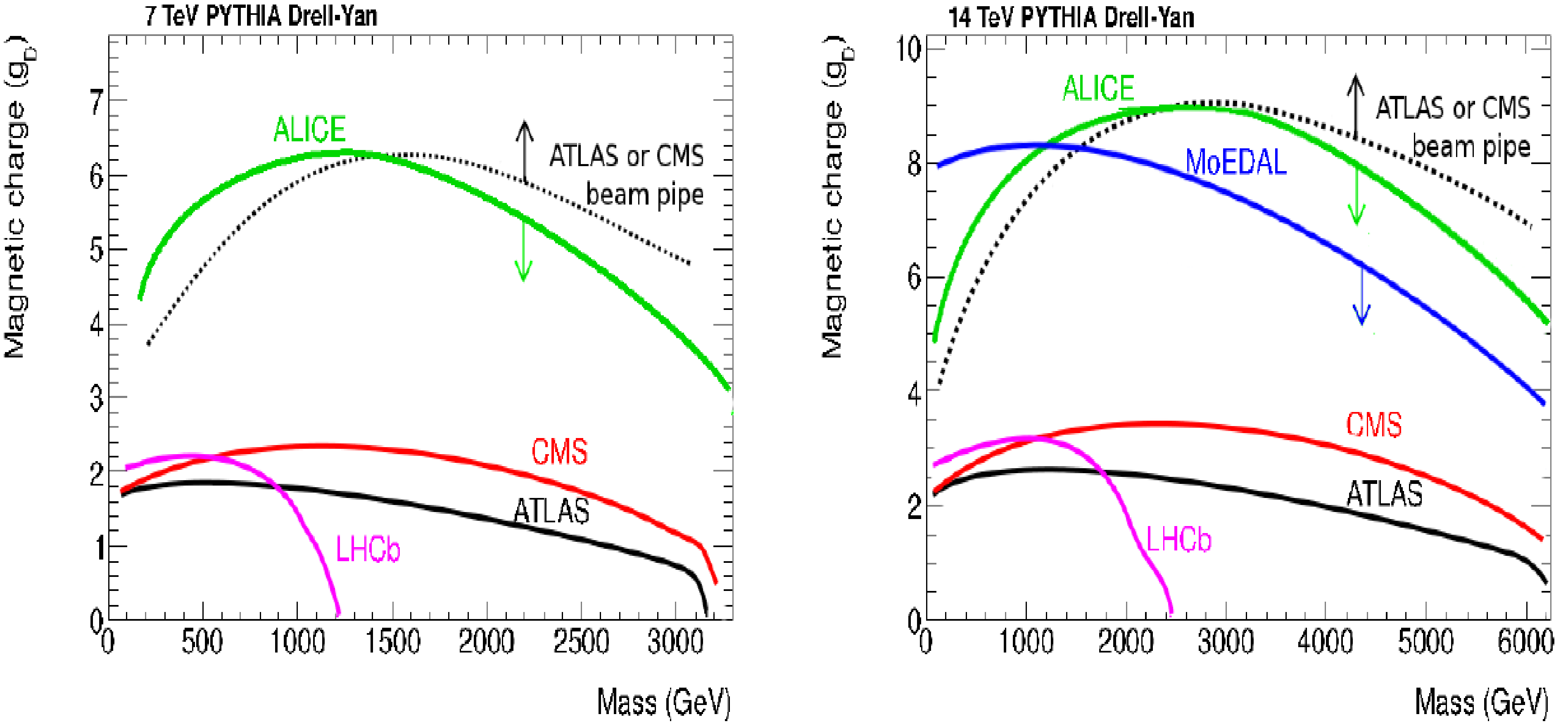




Major source of inefficiency comes from acceptance (punch through) → **Model-independent approach:** 1-2 pb limits set in well-defined kinematic ranges

Sequel: monopole search with 2011 data currently being approved by the Collaboration → with dedicated reconstruction and simulation

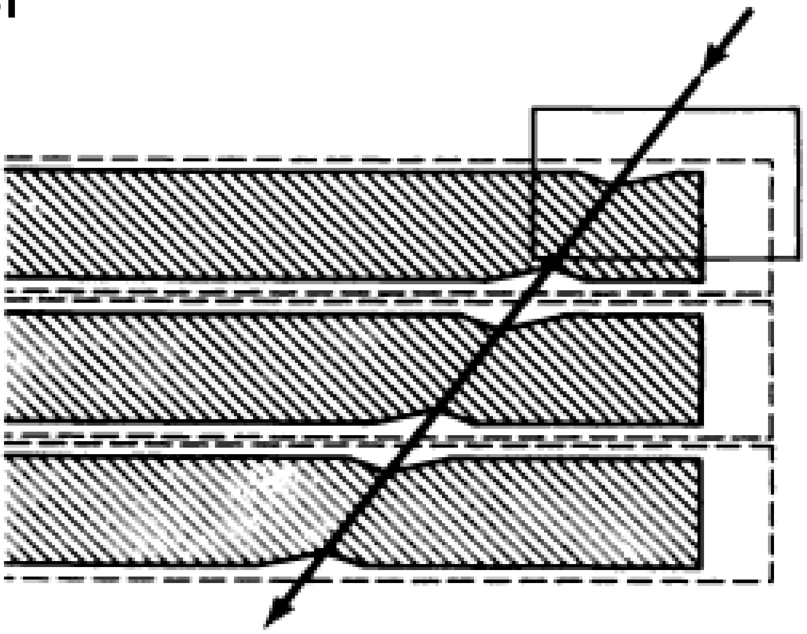
LHC reach in mass and charge



Old (460 Myrs) 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
- $F < 10^{-18}\ cm^{-2}s^{-1}sr^{-1}$

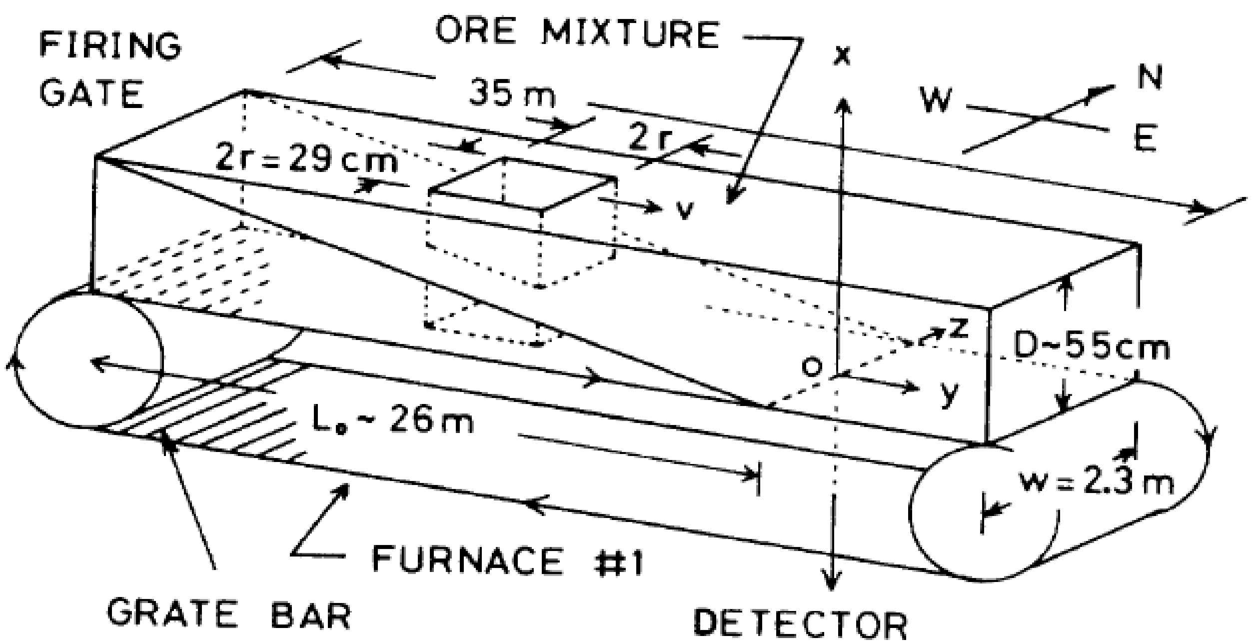
PRL 56, 1226 (1986)



Iron ore

- Induction detector placed under a furnace at ore-processing plant
  - Large amounts (>100 tons) of material
  - Assume ferromagnetic binding, but **must also assume no binding to nuclei**
- $\rho < 10^{-30}$ monopoles/nucleon

PRD 36, 3359 (1987)

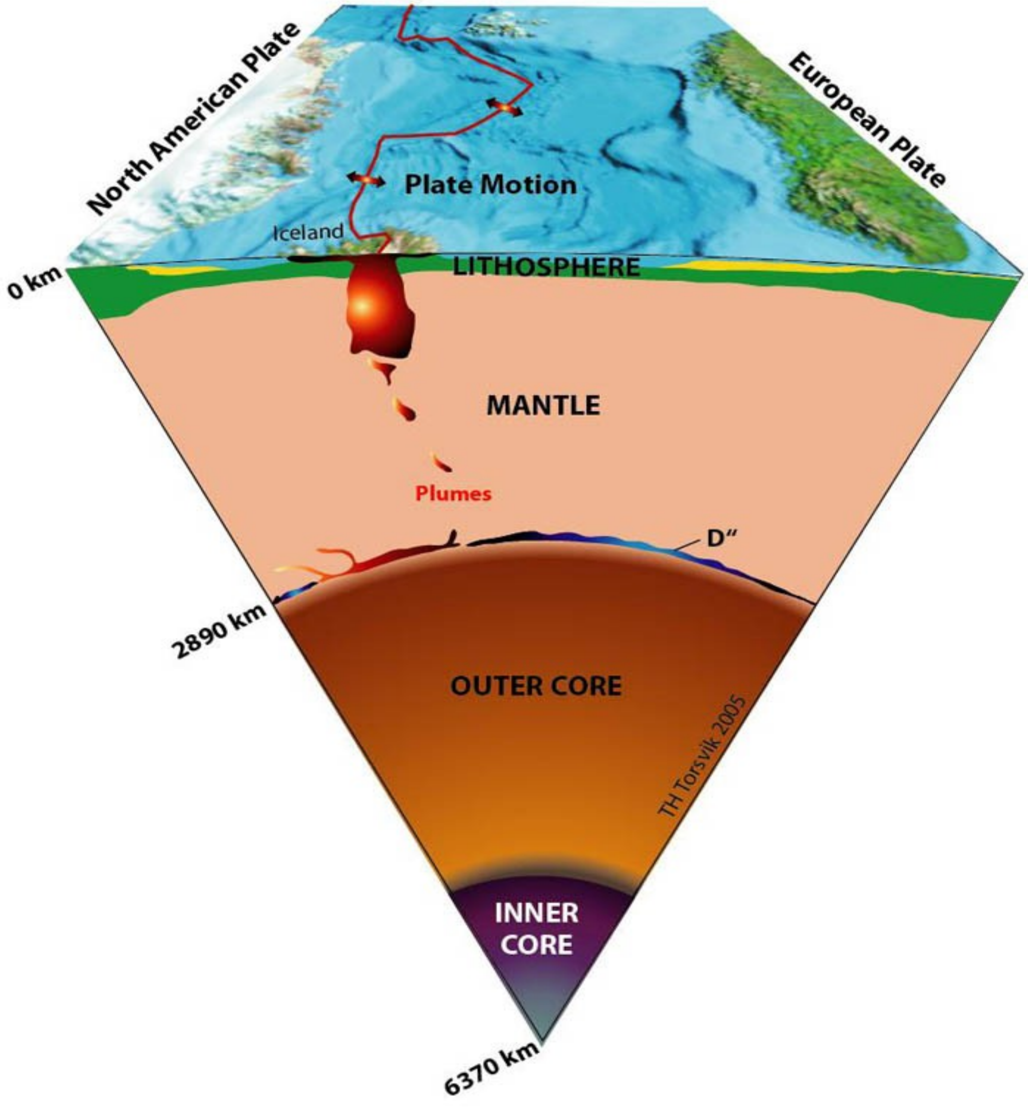


Deep-sea sediments (extraction)

PRD 4, 1285 (1971)

- Where would monopoles have accumulated preferentially?
- Monopoles thermalised in ocean water would drift to the bottom and become trapped near the surface of sediment
  - Sedimentation rate 0.1 – 1 mm/century
- Unfortunately the extraction method used in this search could only probe masses up to 10^4 GeV

“Hot spot” plume in the Earth's mantle



Annihilation of monopoles inside Earth

- Heat generation from monopole-antimonopole annihilations during geomagnetic reversals
- $\rho < 10^{-28}$ monopoles/nucleon

Nature 288, 348 (1980)