New limits on Magnetic Monopole searches from accelerator and non-accelerator experiments

M. Cozzi

Bologna University

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Outline

- Introduction:
  Why experiments search for Magnetic Monopoles?
- Properties of Magnetic Monopoles (MMs)
  - Classical "Dirac" MMs
  - GUT MMs
- MMs searches with accelerator experiments
  - recent results and ongoing analyses
- GUT MMs searches with cosmic rays
  - new limit from the SLIM experiment
- Conclusions

Why experiments search for magnetic monopoles?

- First hint:

If Magnetic Monopoles exist, Maxwell's equations become symmetric.

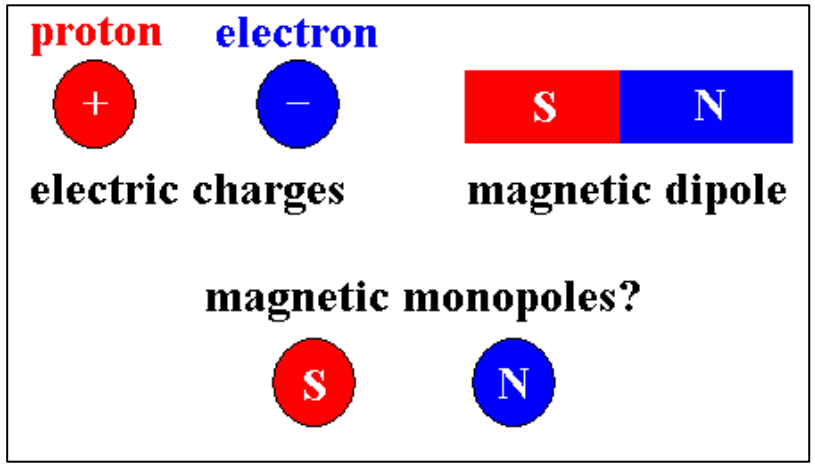
$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \vec{B} = \mu_0 \rho_m$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \mu_0 j_m$$

$$\nabla \times \vec{B} = \mu_0 \vec{j} + \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

$$F = e\left(\vec{E} + v \times \vec{B}\right) + g\left(\vec{B} - \frac{1}{c^2}(v \times E)\right)$$



Classical magnetic monopoles

- Second hint: Dirac, 1931

If Magnetic Monopoles exist, the electric charge is automatically quantized: "Dirac quantization condition"
[Proc. R. Soc. London, 133 (1931) 60]

$$eg = n\frac{\hbar c}{2}, \quad n = 1,2,3,\ldots$$

$$g = n\,g_D = n\frac{\hbar c}{2e} = \frac{137}{2}e, \qquad \left(\frac{\hbar c}{e^2} = 137\right)$$

The theory doesn't predict the monopole mass. It could be very low!

Dirac, with classical considerations, estimated the MM mass:

$$r_e = \frac{e^2}{m_e c^2} = r_M = \frac{g^2}{m_M c^2}$$

$m_M \approx 2.4$ GeV/c²

Many searches with accelerators

GUT magnetic monopoles

- Third hint: 't Hooft and Polyakov, 1974

The Higgs field in a non-abelian gauge theory (NAGT) would produce Magnetic Monopoles when the theory brakes into U(1).
[Nucl. Phys. Rev. 29B (1974) 276 and JEPT Lett. 20 (1974) 194]

The mass of primordial MM is related to the relevant gauge symmetry breaking scale:

SU(5) + SUSY predicts $m_{MM} = 10^{16} - 10^{17}$ GeV

Other GUT scenarios predict MM mass $m_{MM} = 10^4$ GeV and lower…

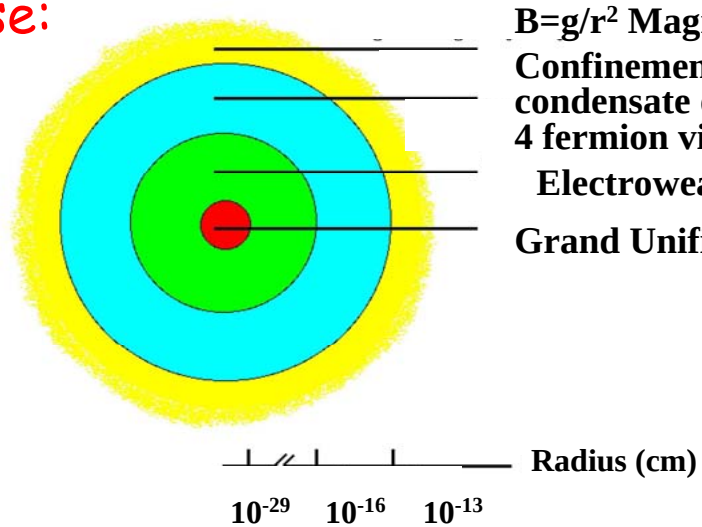
- Fourth hint: "colored monopoles"

Magnetic Monopoles are candidate for agents of confinement in QCD and other NAGT 's ['t Hooft, Nucl. Phys. Rev. 190B (1981) 455]

GUT Monopoles

GUT MMs are extended objects.

SU(5) case:



$B=g/r^2$ Magnetic field of a point Dirac monopole

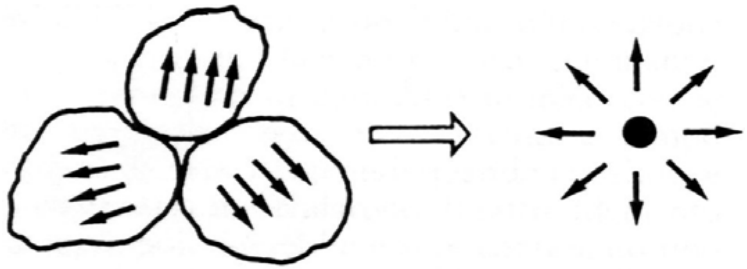
Confinement region: virtual γs, gluons, condensate of fermions -antifermion, 4 fermion virtual states

Electroweak unification: W, Z

Grand Unification: virtual X,Y

Production:

as topological defects (t~ 10^{-35} s)



May be present today in the Cosmic Radiation as "relic" particles

Properties of Magnetic Monopoles

- Magnetic Charge

  If n = 1 and e = electron charge

  $g_D = \hbar c / 2e = e/2\alpha = 68.5\ e$ (If free quarks exist: $|e|=1/3 \rightarrow 3\ g_D$)

- Electric charge = 0
- Coupling constant $\alpha_M = g^2_D/\hbar c = 34.25$
  - ✓ perturbative field theory cannot be used
  - ✓ ionization energy losses will be several order of magnitude larger for MMs than for MIP electrically charged
- Energy gain in a magnetic field $W = n\ g_D\ B\ L = n\ 20.5$ keV/G cm

  In a coherent galactic length: (L= 1 kpc and B = 3 μG) $W \cong 1.8 \times 10^{11}$ GeV

  - ✓ Classical MMs and light MMs in the CR may be accelerated to relativistic velocity.
  - ✓ GUT MMs would have lower velocity.

Searches for MMs up to now

Direct experiments:

A large variety of devices to detect the signature of MM passage:

- Searches in Cosmic Rays
- Searches for monopoles which stop in matter (as in lunar rocks)
- Searches for Magnetic Monopoles at colliders

Indirect experiments:

Measurements of multi-photon production in collider experimet

Searches at accelerators:

Cross section upper limits vs MM mass

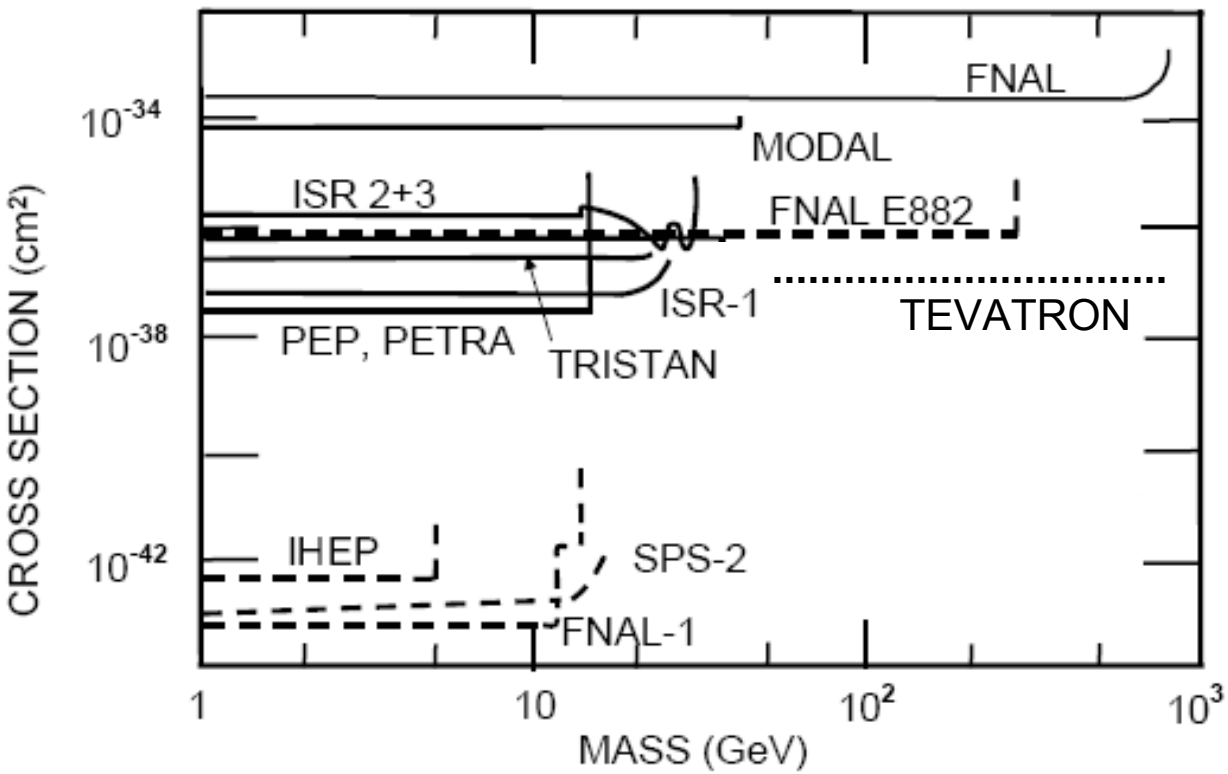
Searches in Cosmic Rays:

Flux upper limits vs MM velocity

Searches for Monopoles at accelerators

Searches at accelerators
present situation

$e^+e^- \to M\,M\,,\quad \bar{p}p \to M\,\overline{M}\,,\quad p\,p \to p\,p\,M\,\overline{M}$



Many limits are model dependent !

Tracking devices — — — MM stopped, extracted and detected or indirect searches

Recent results:
Ms direct search at HERA (H1 Coll.)

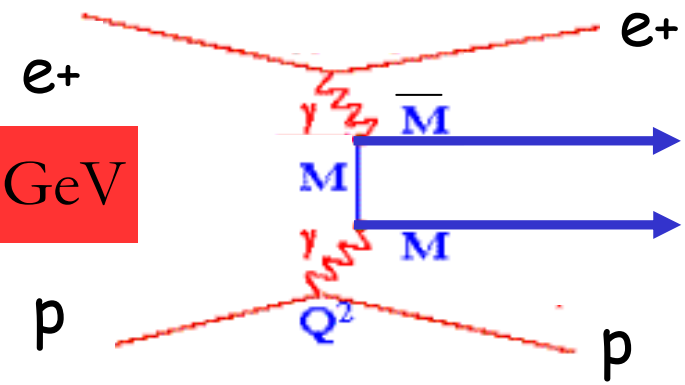
The first direct search for Monopoles produced in e^+p

Two models:

$$e^+ p \rightarrow M\,\overline{M}\;\; e^+ p$$

$$e^+ p \rightarrow M\,\overline{M}\;\; e^+ X$$

$$\sqrt{s} = 300\ \mathrm{GeV}$$

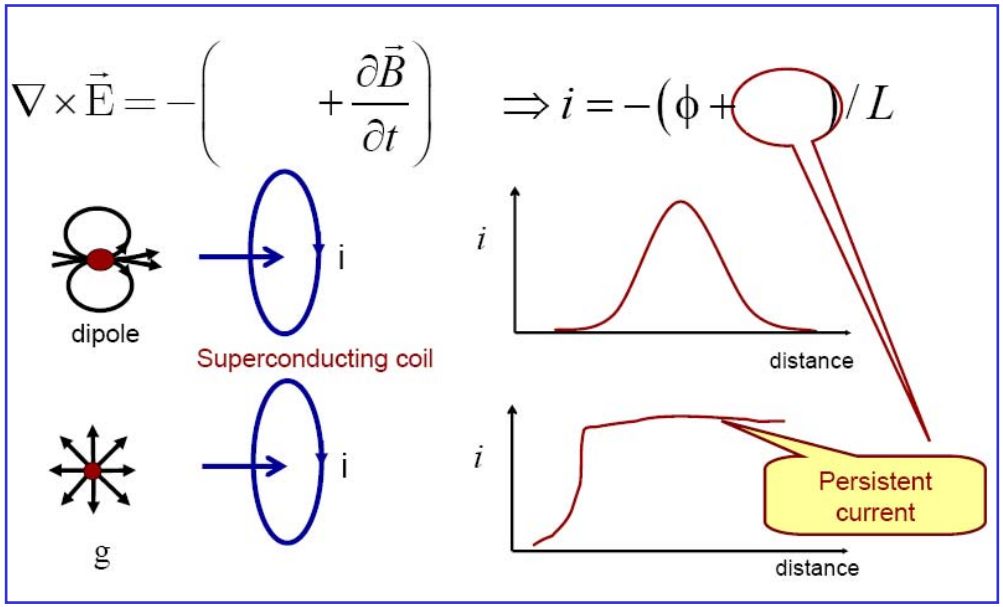


MMs
- Production time range: 1995 – 1997
- Stopped in the beam pipe surrounding the H1 interaction point
- Trapped (they are stable)

Later
- The beam pipe was cut into long strips
- MM detected with a superconducting coil (SQUID magnetometer)

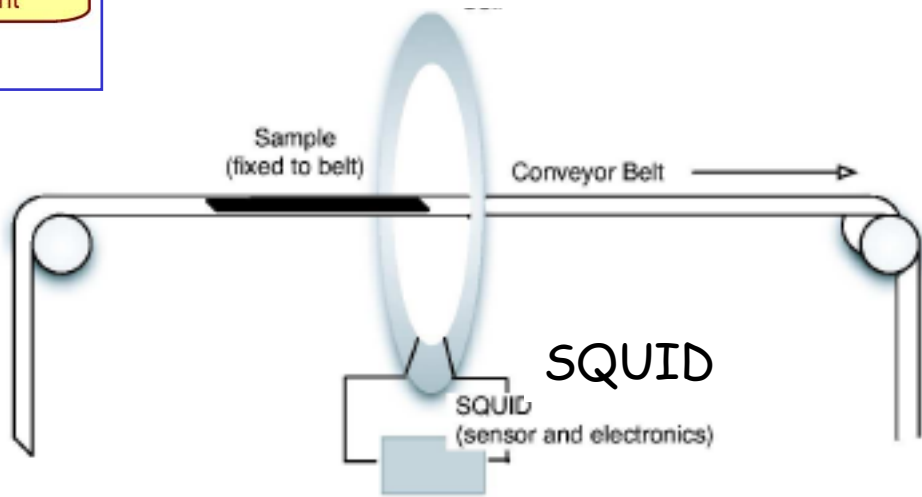
Luminosity = 62 ± 1 pb^{-1}

Experimental technique



MMs "detector"

Superconductin coil

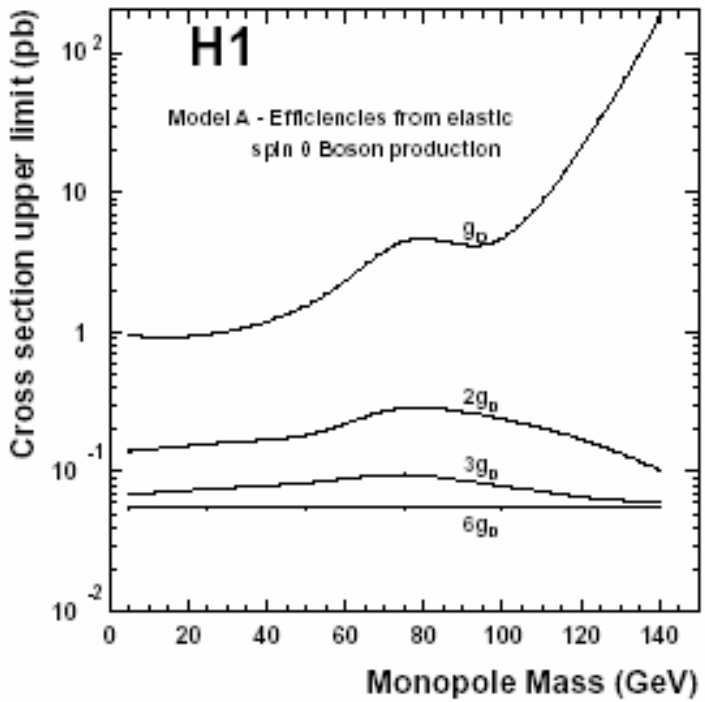


No monopole signal

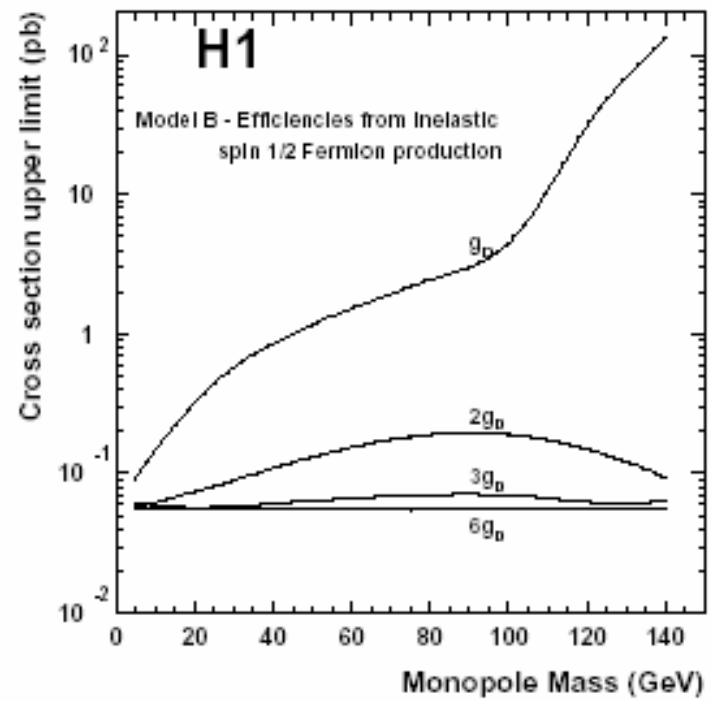
Model dependent upper limits for monopole pair production m_M<150 GeV and charge g = 1-6 g_D

Model dependent upper limits on cross section

MM as a Boson



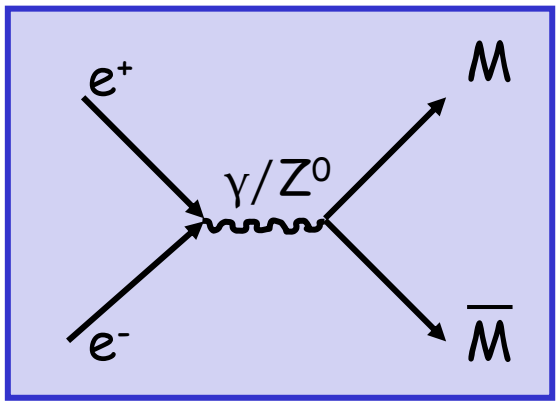
MM as a Fermion



H1 collaboration : hep-ex/0501039

Search for MMs with the OPAL detector @ LEP

A new direct search for pair-produced MMs has been performed with the OPAL detector by using the jet chamber (CJ) as a tracking device.



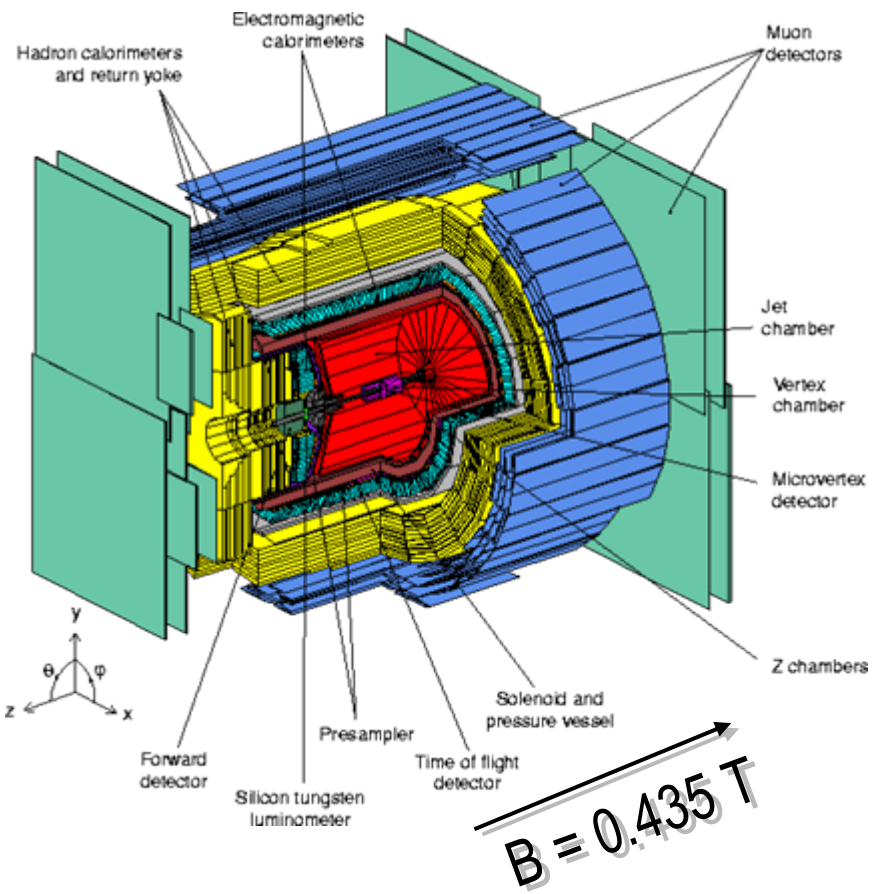
cross-sectional advantage over a search at hadron colliders

(no large radiative corrections)

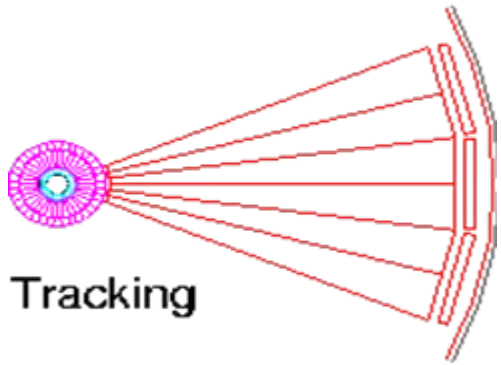
Model independent analysis:

only based on the high ionization in the CJ

The OPAL detector



JET CHAMBER (CJ):



Cylindrical drift chambers:

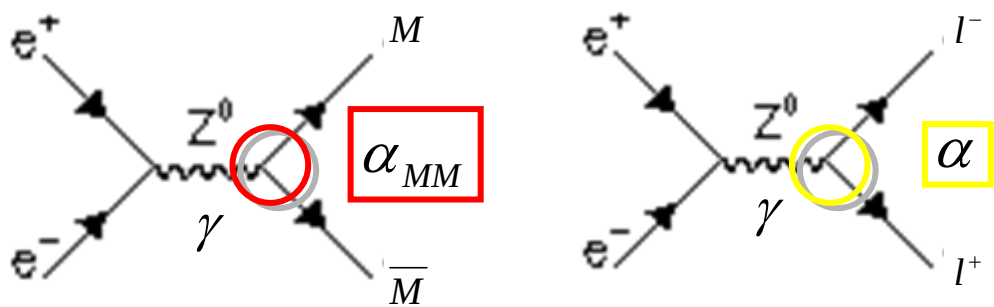
- coordinate → tracking
- curvature → momentum
- dE/dx → particle ID

Monte Carlo simulation

Assuming

$$\alpha_{MM} >> \alpha$$

$$m_{MM} > \frac{m_{Z^0}}{2} = 45\,GeV$$



MM simulation:

1. Uniform azimuthal distribution

   and (1 + $\cos^2\theta$) polar angle distribution (MM as fermion)

2. MM trajectory in the CJ obtained from the Lorentz force:

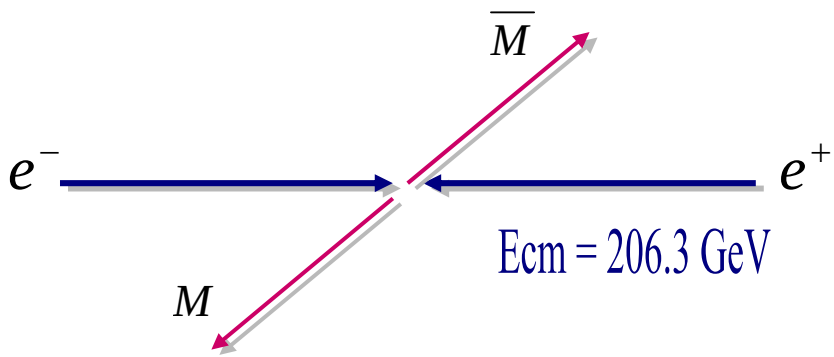
$$\begin{cases} \vec{B} = B \cdot \hat{z} \\ \vec{F} = g\left(\vec{B} - \vec{v} \times \vec{E}\right) \end{cases}$$

3. Monopole mass from 45 GeV to 104 GeV ($\sqrt{s} = 208\,GeV$)

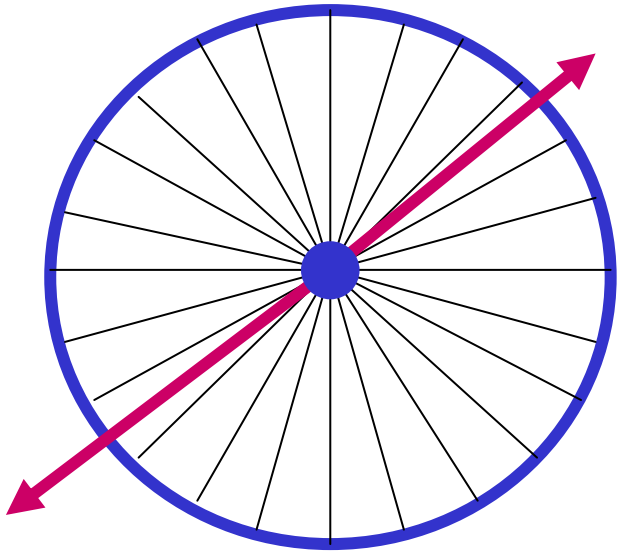
   (each sample contains 1000 events)

Analysis strategy

$e^+e^- \rightarrow M\,\overline{M}$



CJ sectors



MM signal topology

- Back-to-back tracks

  → two opposite CJ sectors with an high energy release

- High ionization

  → most CJ hits contain enough charge to create an overflow

Data Analysis

Sub-sample of LEP2 data collected when single hit acquisition was ON

$$\sqrt{s} = 206.3\ GeV$$

$$L = 63\ pb^{-1}$$

Good signal selection efficiency for monopoles with:

- $g \geq g_D$
- m_M: 45 ÷102 GeV

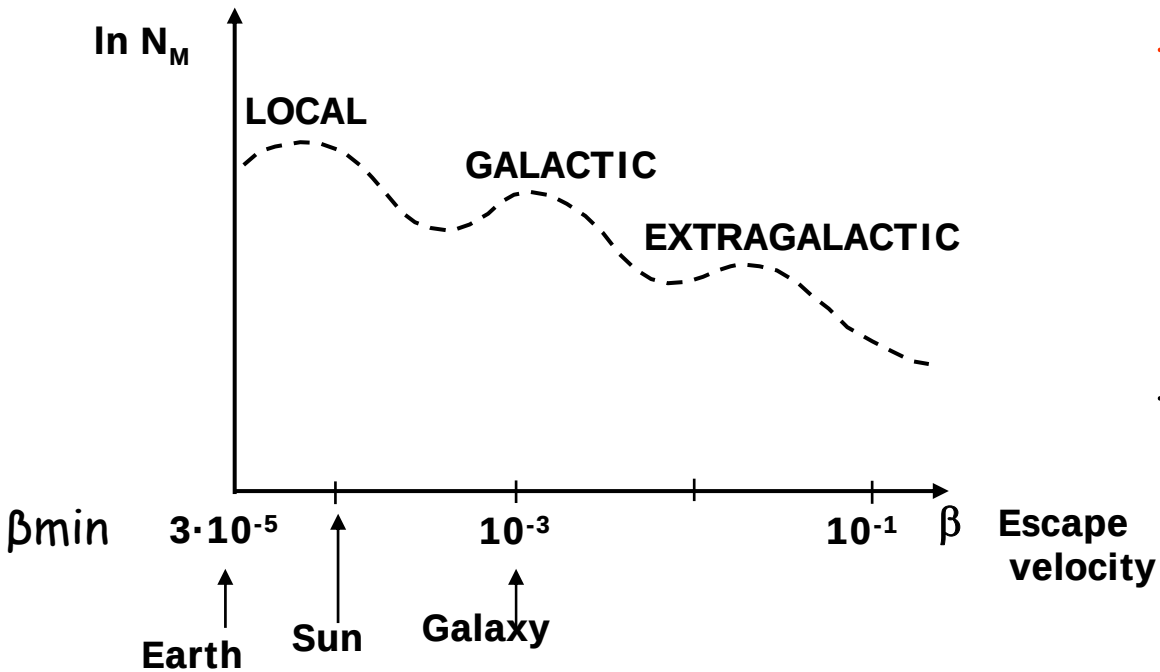
We are able to set a competitive (model-independent) cross-section upper limit on pair-produced Magnetic Monopoles.

Results coming soon !

Searches for Monopoles in Cosmic Rays

Searches in Cosmic Rays

Expected MM velocities are related to the escape velocity of the system in which they are confined



- No predictions from Cosmology on MM flux

- Upper limits on MM fluxes put constraints on some cosmological models

Astrophysical limits
on Magnetic Monopole flux

- Survival of galactic magnetic fields
  "Parker Bound" (TPB)

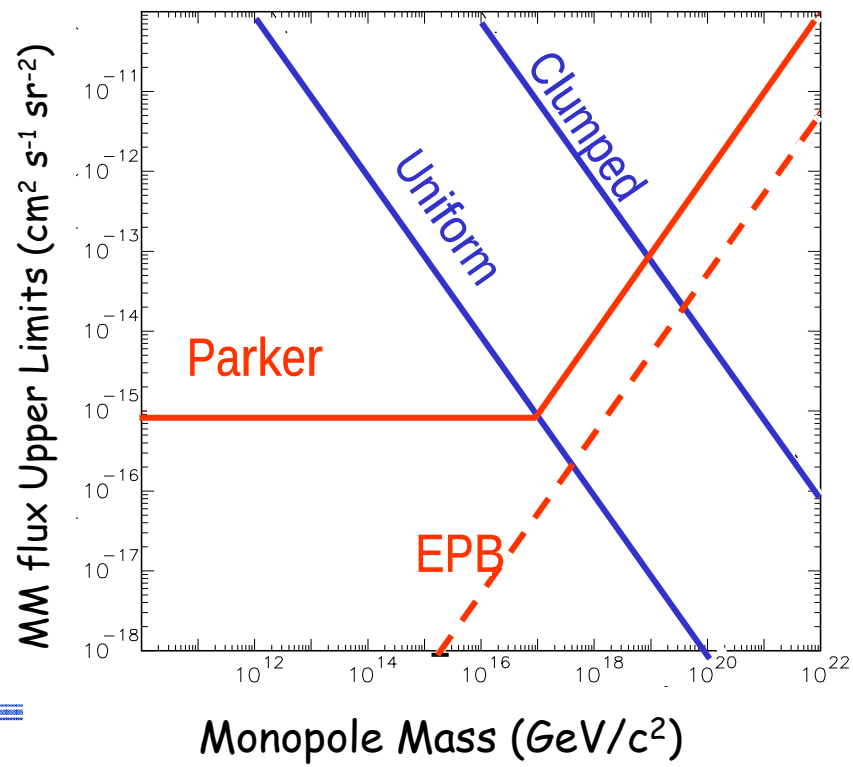
$\Phi_{TPB} < 10^{-15}\ cm^{-2}\ s^{-1}\ sr^{-1}$ for $\beta < 3\ 10^{-3}$
$\Phi_{TPB} < 10^{-9}\ \beta^2\ m_{17}\ cm^{-2}\ s^{-1}\ sr^{-1}$ for $\beta > 3\ 10^{-3}$

- Survival of early seed of galactical magnetic field
  "Extended Parker Bound" (EPB)

$\Phi_{EPB} < m_{17}\ 10^{-16}\ cm^{-2}\ s^{-1}\ sr^{-1}$

$m_{17} = m_M/10^{17}\ GeV/c^2$

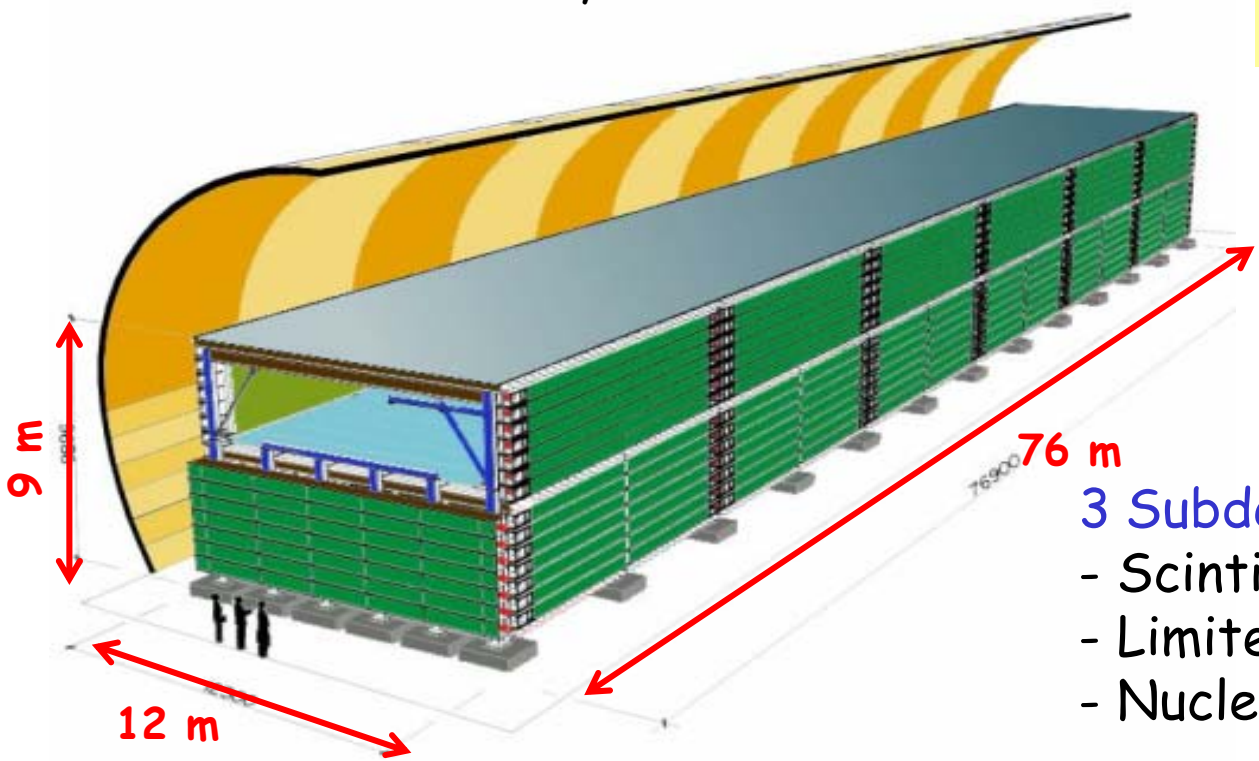
- Limits from Universe mass density
  "uniform" or "clumped"



The MACRO experiment @ LNGS

DATA TAKING from early 1989 to December 2000

$S\Omega$ ~10000 m^2sr



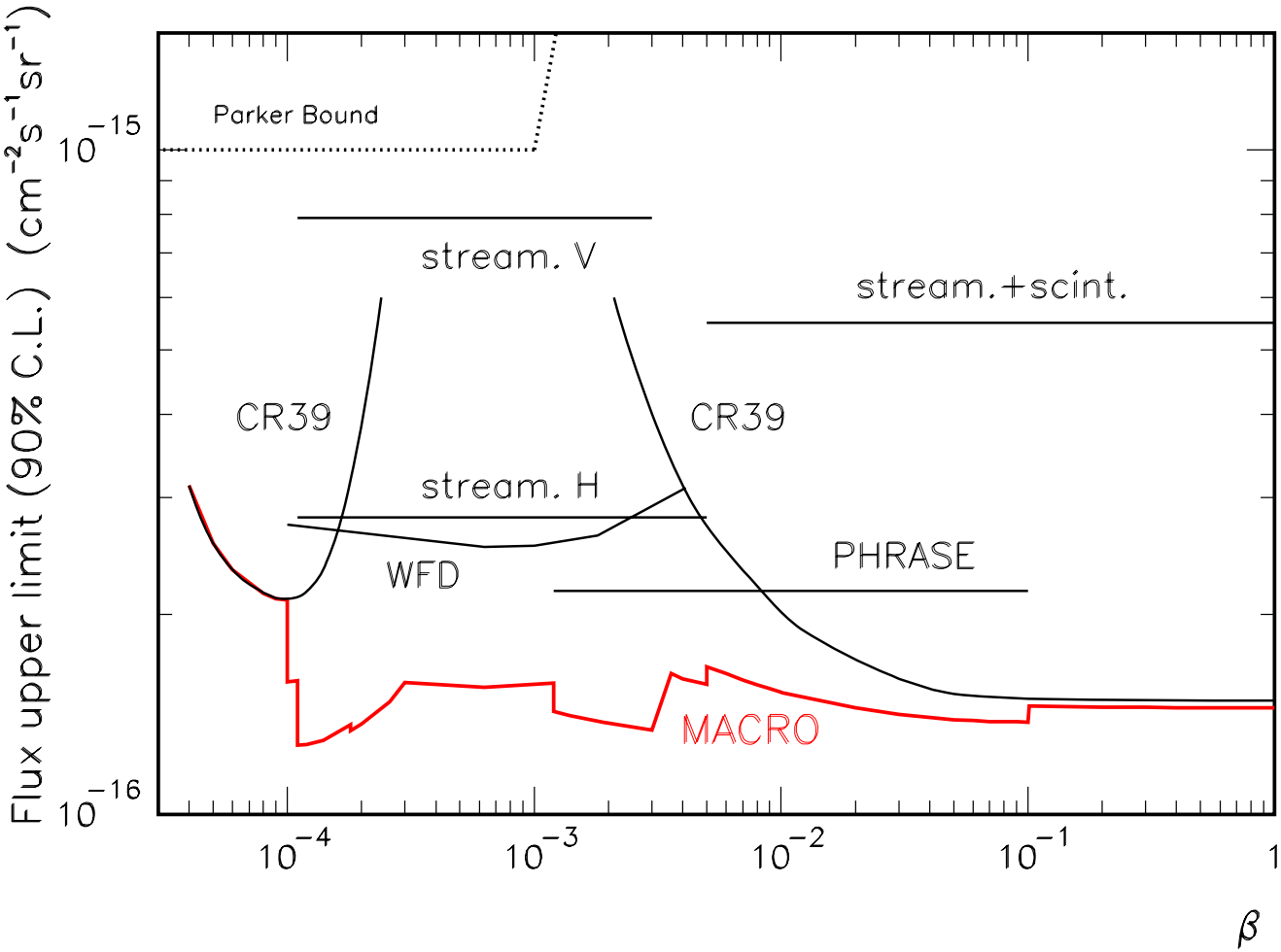
3 Subdetectors:
- Scintillation Counters
- Limited Streamer Tubes
- Nuclear Track Detectors

Different analysis techniques were used for various β regions, by using the three subdetectors

Redundancy & Complementarity

MACRO: Final results

EPJ C25 (2002) 511

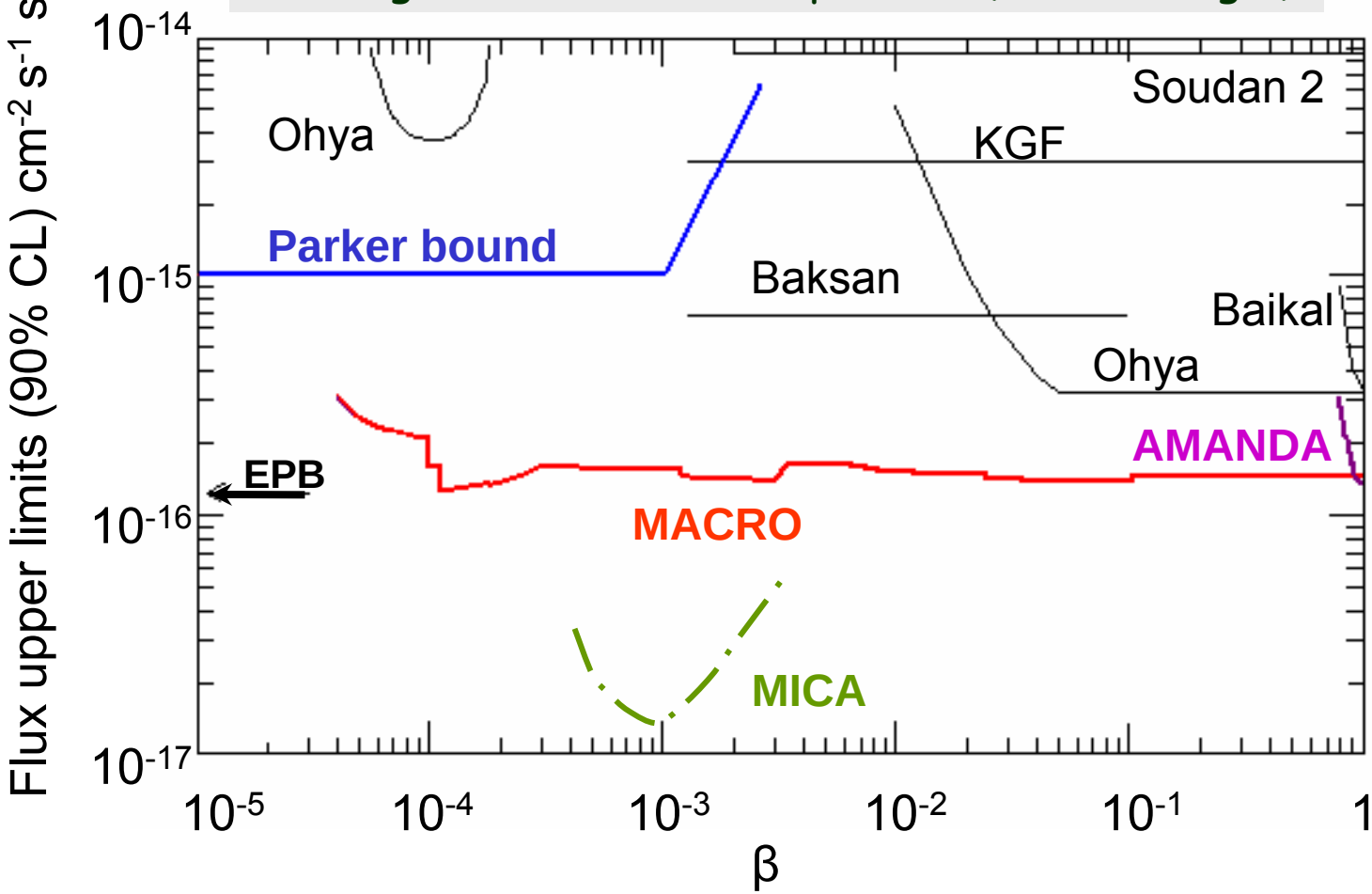


$g = g_D$

$\sigma_{cat} < 1$ mb

Searches with cosmic rays
present situation for heavy MM

For large masses → Isotropic flux (4π solid angle)

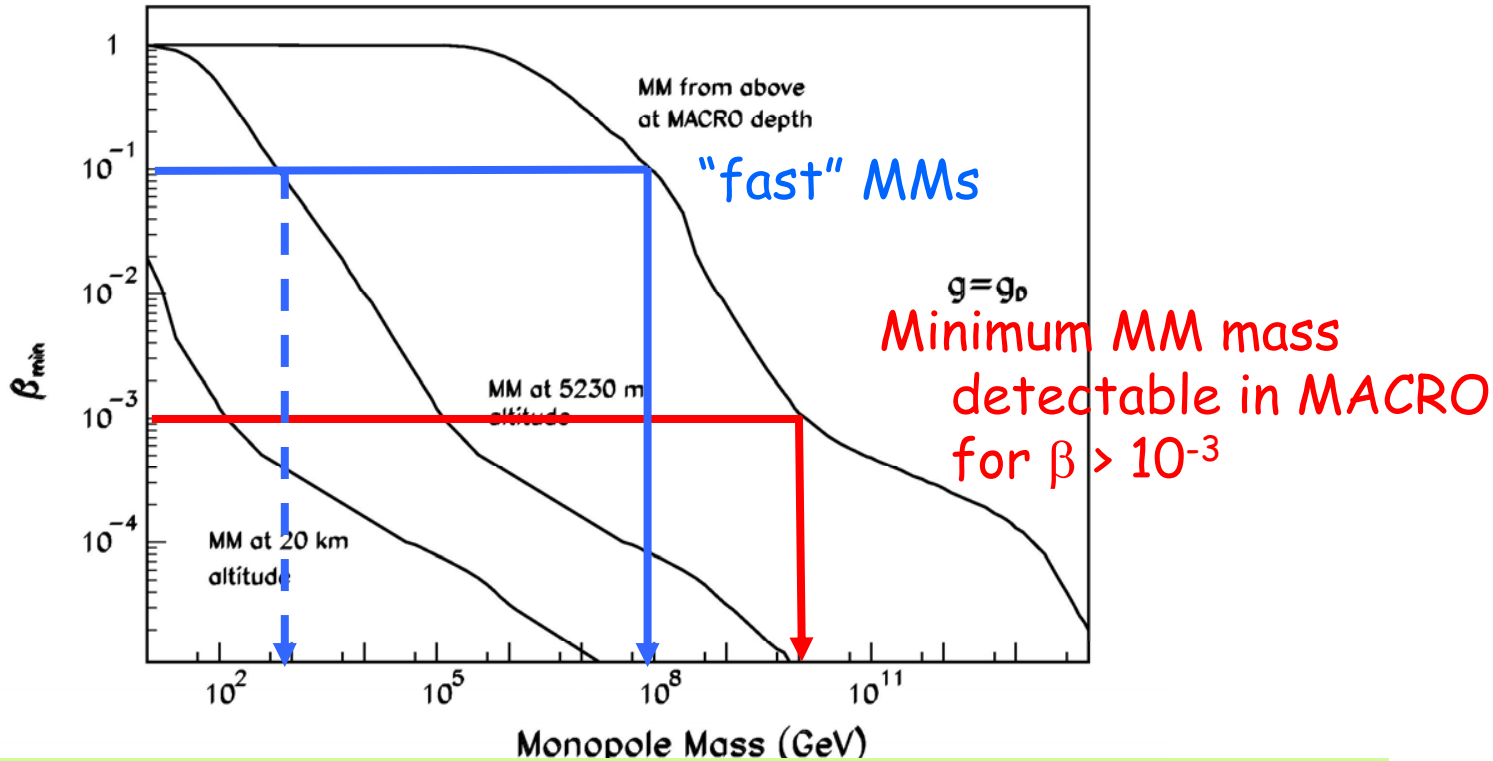


$g = g_D$

$\sigma_{cat} < 1$ mb

Searches for light MMs

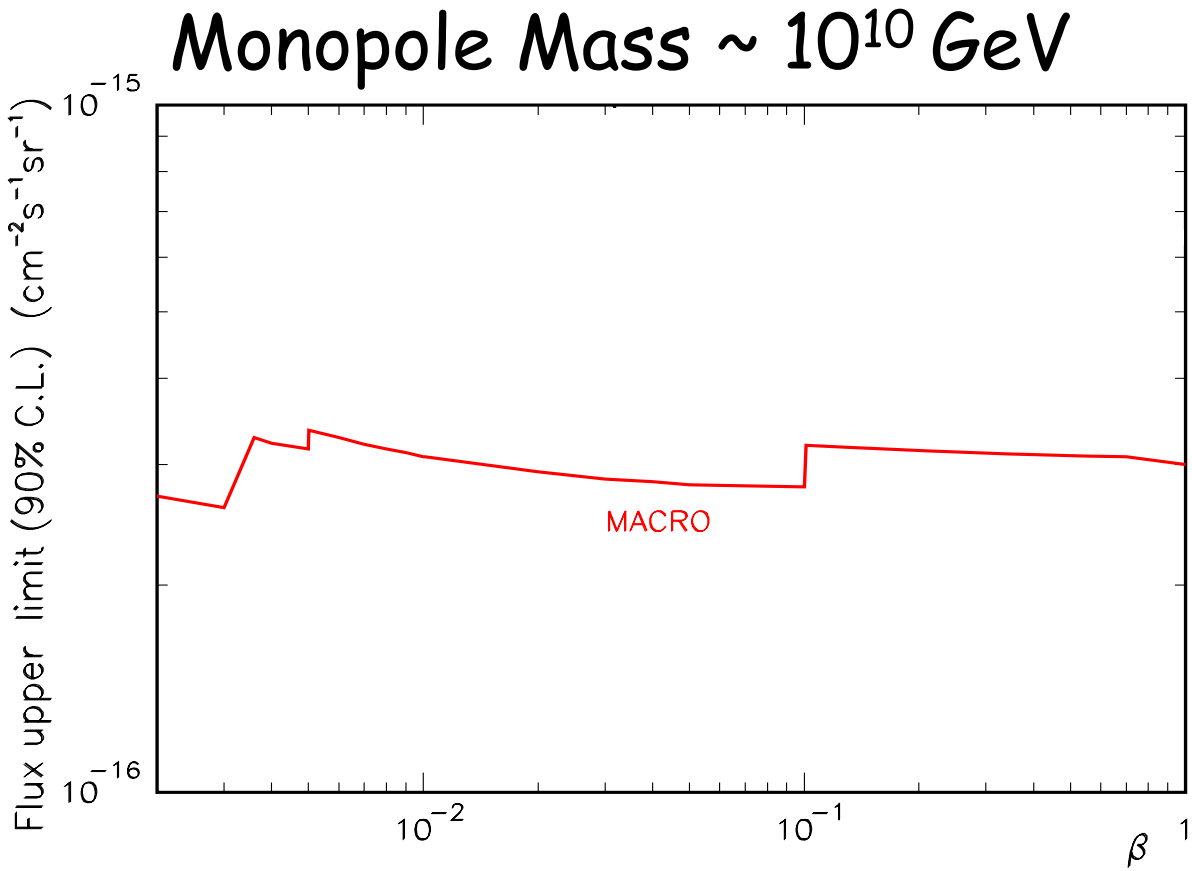
For "light" MMs, acceptance ≠ 4π: they could slow down, go under threshold and/or be trapped in the Earth



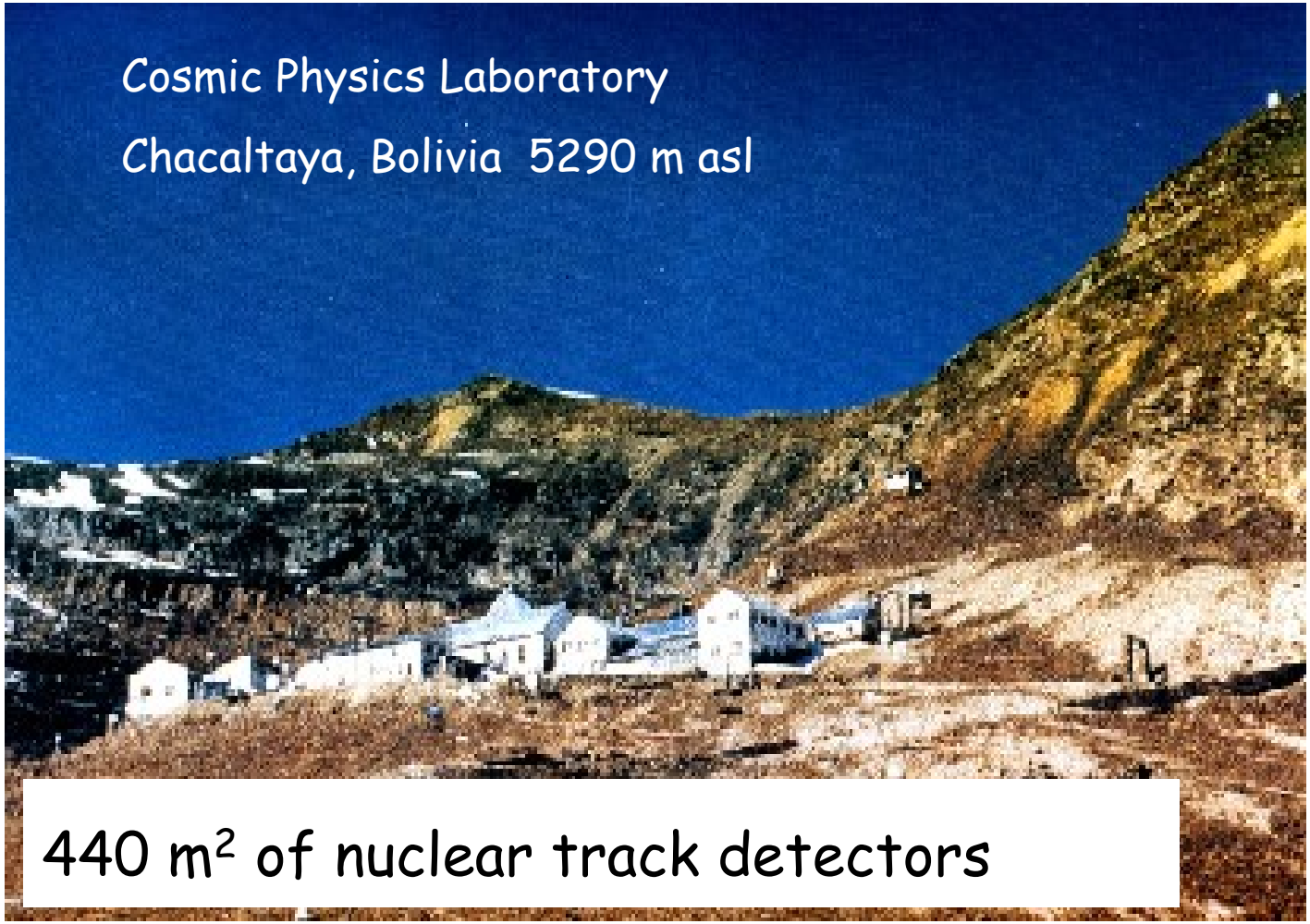
Accessible regions in the plane (mass, β) for MMs coming from above for an experiment at high altitudes and underground.

Searches with cosmic rays

MACRO results for light MMs

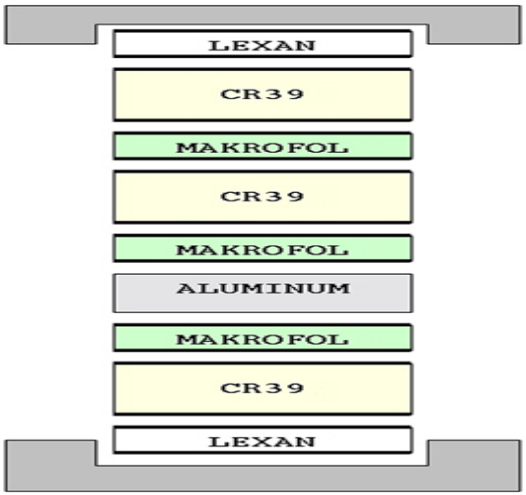


The SLIM experiment

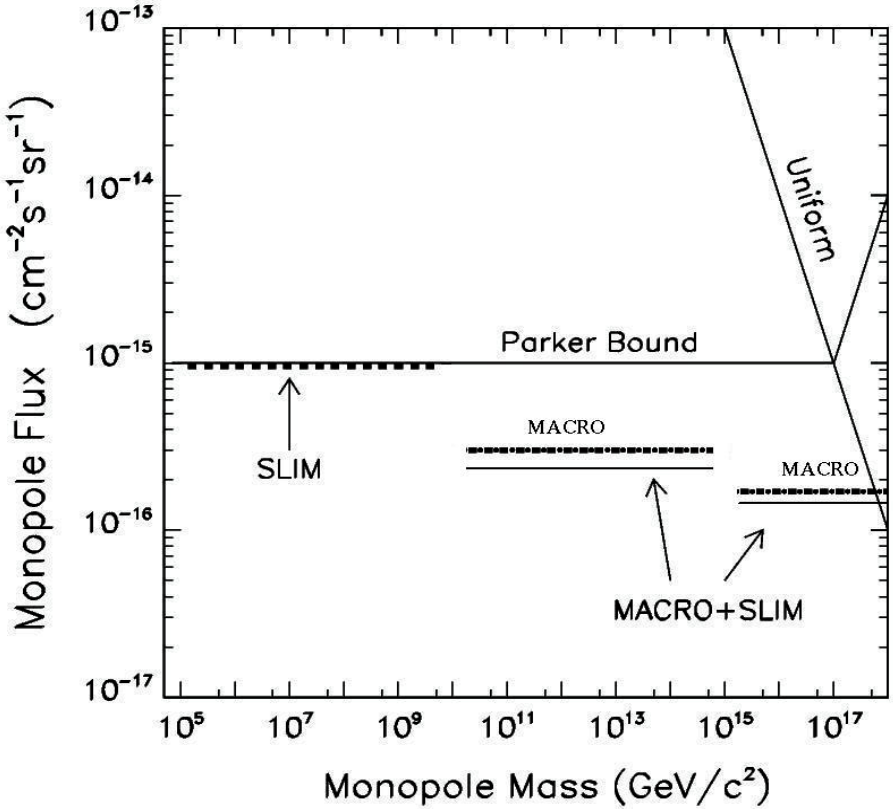


440 m^2 of nuclear track detectors

The SLIM detector layout @ Chacaltaya

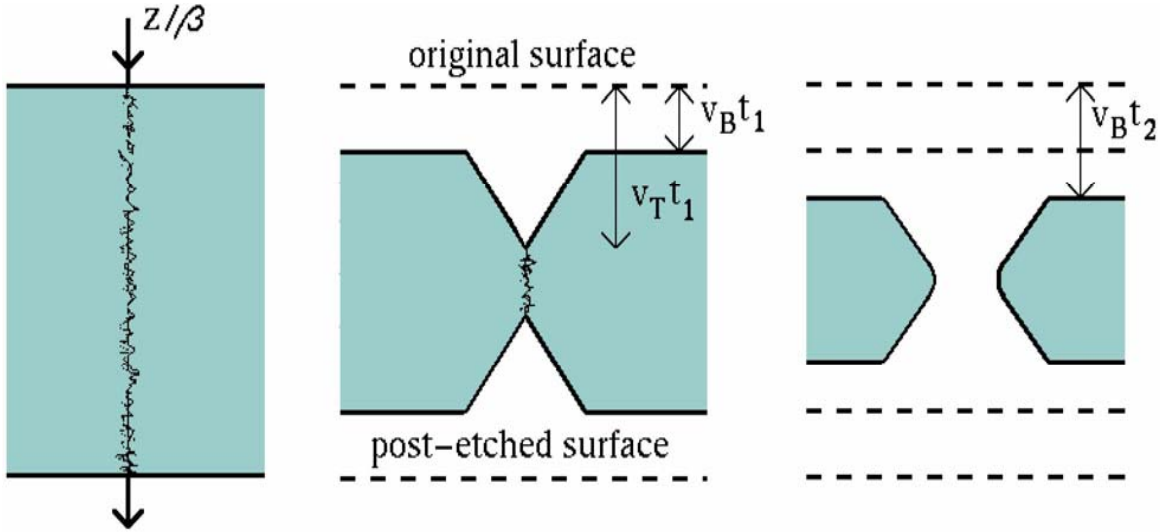


Modules 24 x 24 cm²

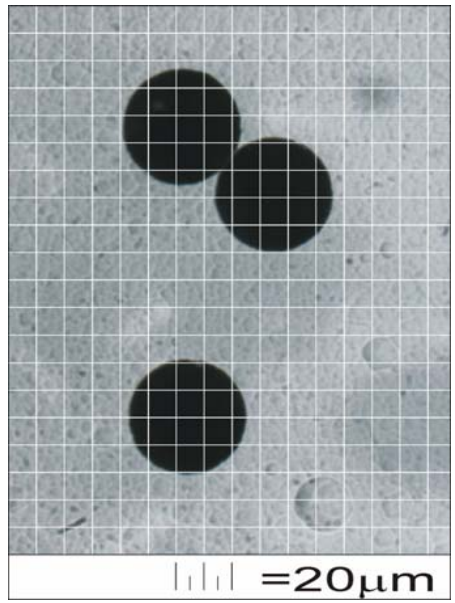


90% CL flux upper limits vs MM mass for SLIM (expected, in absence of candidates) and MACRO

The etching procedure



200 A GeV S^{16+}
or
$\beta \sim 10^{-2}$ MM
(soft etching)



Two etching have beed defined:

Strong etching: 8N KOH + 1.25% Ethyl alcohol 77°C 30 h

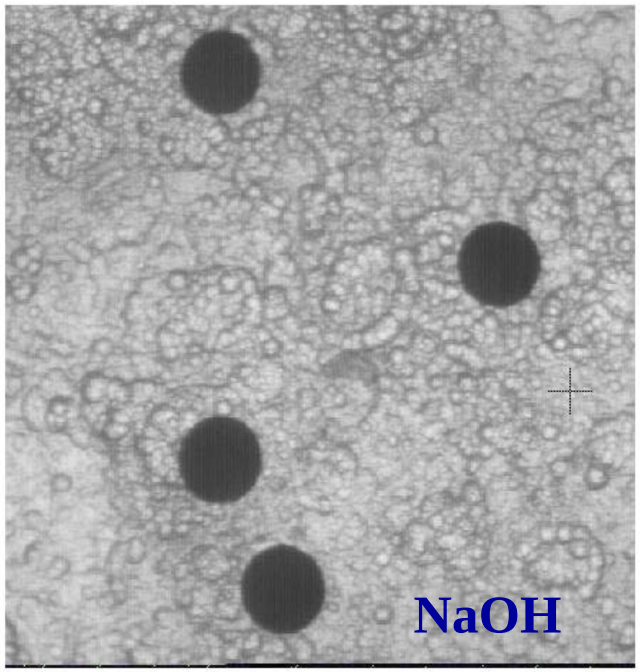
Soft etching: 6N NaOH + 1% Ethyl alcohol 70° 40 h

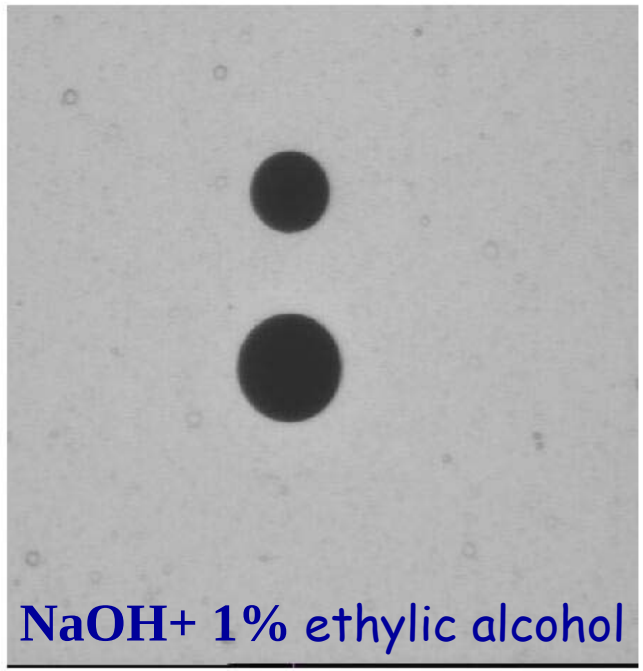
The etching procedure

New etching procedure, different from MACRO

New (very delicate!) etching procedure → higher signal/noise ratio

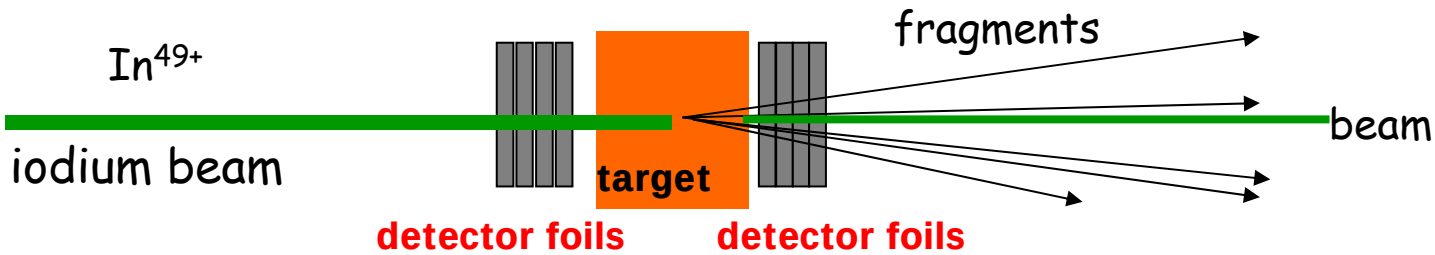
OLD





NEW

CR39 calibration



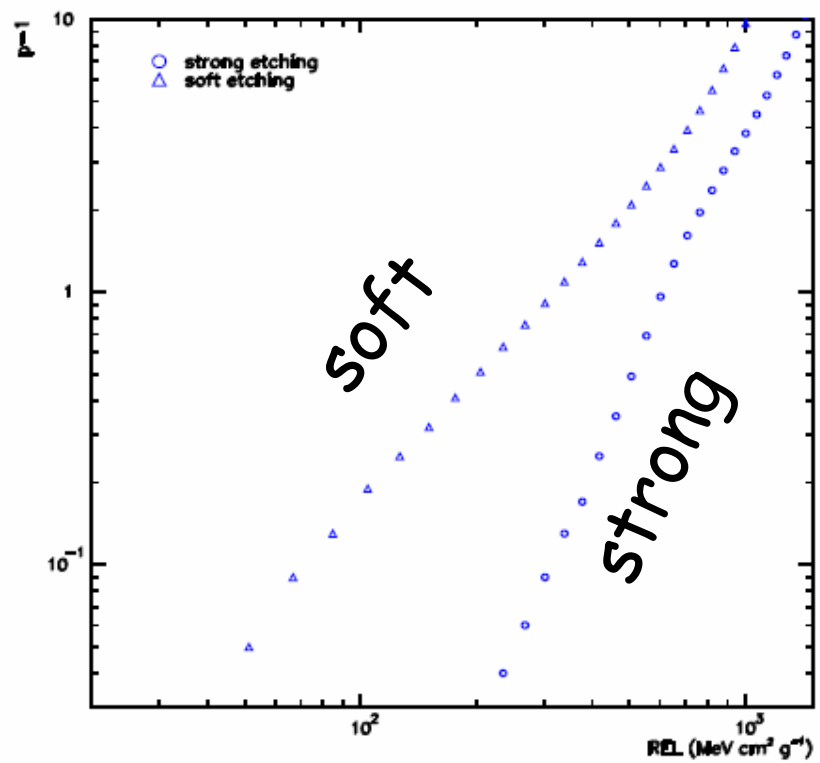
CR39 threshold:

"soft" etching Z/β ~ 7

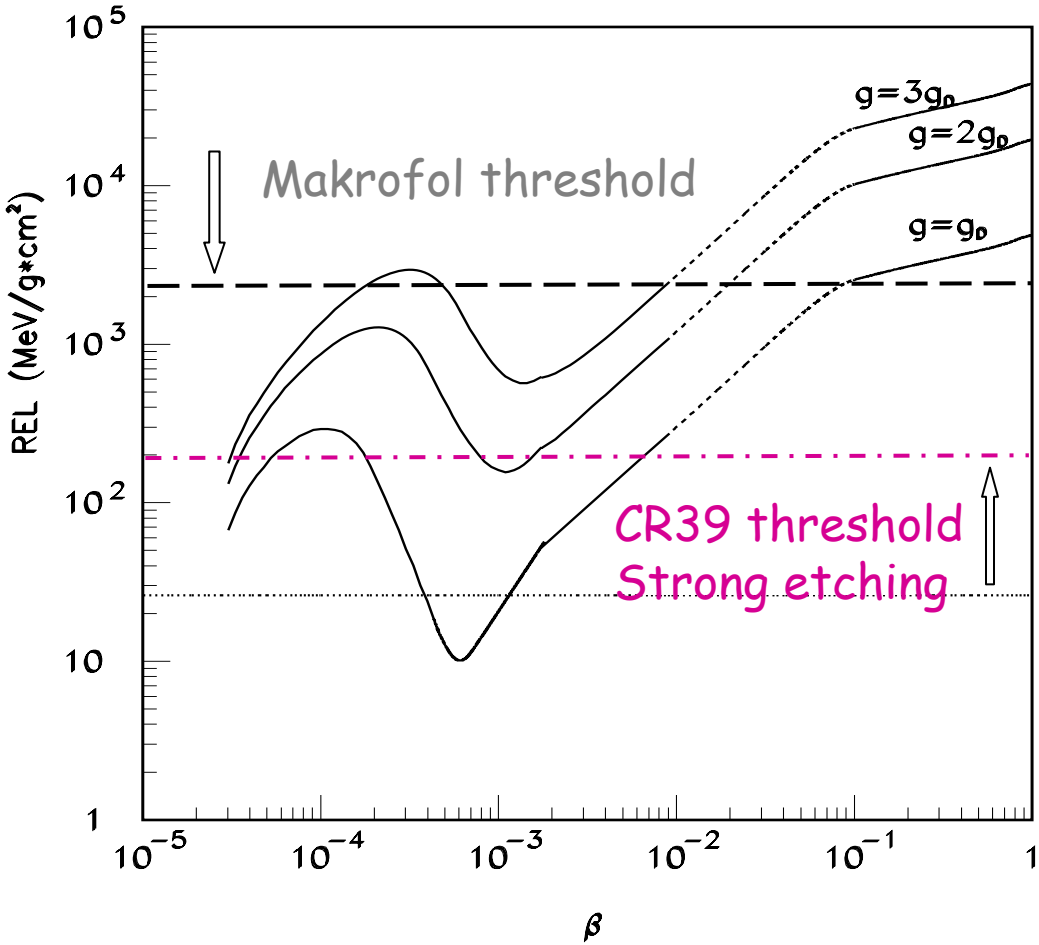
→ REL ~ 50 MeV cm^2 g^{-1}

"strong" etching Z/β ~ 14

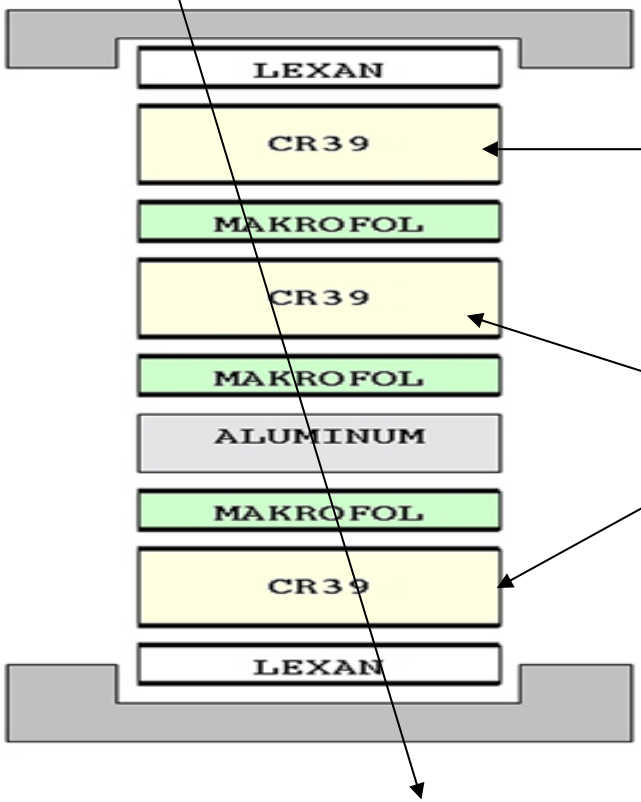
→ REL ~ 200 MeV cm^2 g^{-1}



Restricted Energy Loss vs β for MMs in CR39 and Makrofol



The search technique



Strong etching (large tracks, easies to detect)

General scan of the surface

If a signal is found in the first sheet...

Soft etching

Scan in the predicted position measurement of REL and direction of incident particle.

Up to now, no double coincidences found.

Preliminary results

We analyzed 170/440 m^2 of CR39 after 3.5 years of exposure at the Chacaltaya Lab.

Up to now, no monopoles have been found.

The 90% C.L. upper limits to the flux of MMs with $g = g_D$, $2g_D$ and $3\ g_D$ and $\beta > 10^{-1}$ ($\rightarrow m_M > 10^3$ GeV) is:

$$\Phi < 3.96\ 10^{-15}\ cm^{-2}\ s^{-1}\ sr^{-1}$$

Conclusions

- Research on MMs has shown a remarkable progress since 1931. This is particularly impressive, since no direct evidence of the existence of monopoles has been found.
- Even without such an evidence, strong theoretical motivations continue to legitimate the experimental program in this field.
- By the way, a new evidence for MMs could be just around the corner!