Cosmic Ray Studies with the L3-Cosmics Program at CERN

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"From Colliders to Cosmic Rays"
10 September 2005; Prague

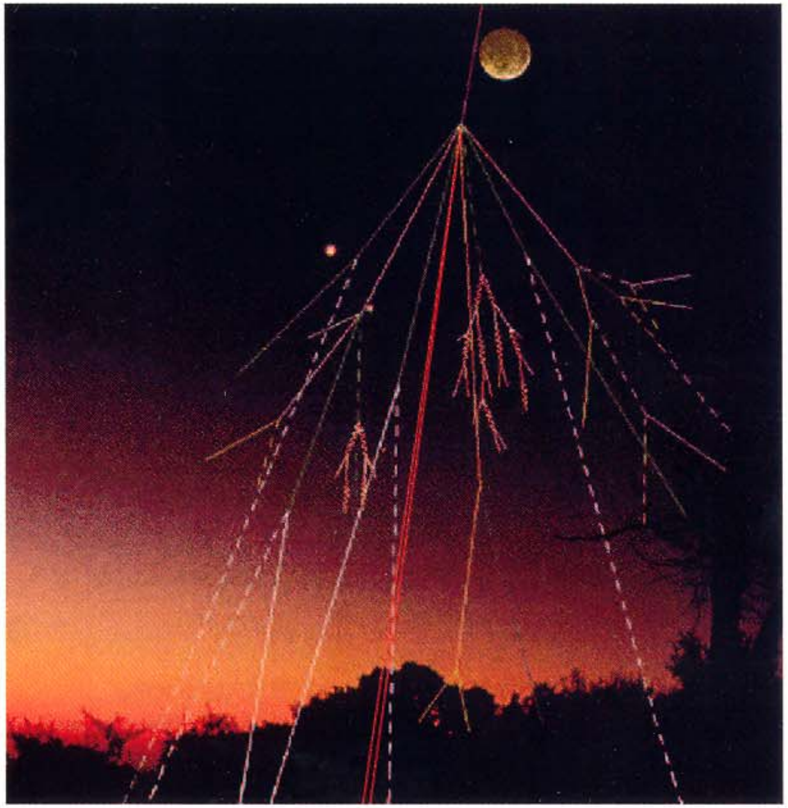
Dr. Travnicek has given a fine introduction to the LEP cosmic ray muon studies. This discussion will focus on the L3-Cosmics program. The L3-Cosmics group, a subset of the larger L3 collaboration, added an independent trigger and data collection system to the L3 detector, so that cosmic ray muon data could be taken independently and in parallel with the LEP electron-positron data. With its large solid angle-area acceptance and high resolution muon chambers, in a 0.5 Tesla magnetic field, the detector had a potential for cosmic ray muon physics much greater than could be justified for only cosmic ray studies.

The following slides are from presentations by Pierre LeCoultre (ETH, Zurich), which he gave at the conference "Beyond Einstein, Physics for the 21st Century"
(Berne, Switzerland in June)
and at the
29th International Cosmic Ray Conference (Pune, India in August).

Note: In this discussion, the study of multi-muons will not be included, as Dr. Travnicek has fully covered that part of the LEP activities. Actually, although the admittance of L3 was larger than ALEPH or DELPHI, the handling of high multiplicity muons was not as simple, and manual scanning of the data is necessary for achieving an accurate count of high-multiplicity events. The IHEP (Beijing) group is still working on this, and final multiplicity distributions, etc., from L3-Cosmics are not yet available.

Cosmic Ray Muons, Antiprotons, VHE Gamma Rays and Sources - Results from L3+C at CERN

Pierre Le Coultre, ETH

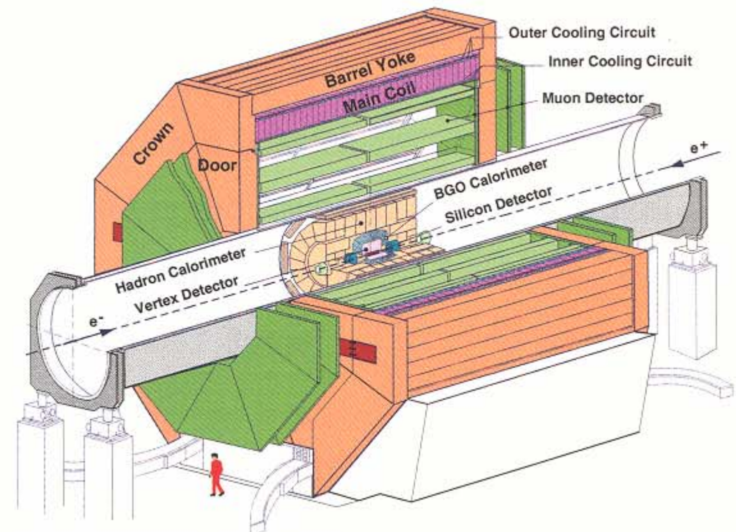


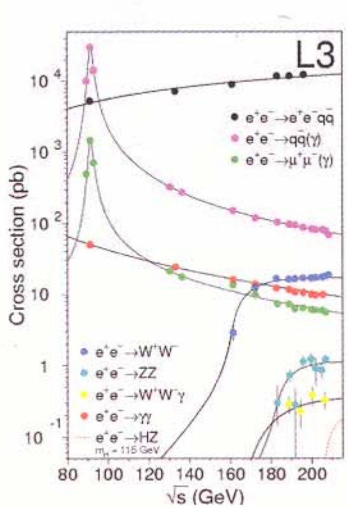
- **L3+C:**
  - A new class of telescopes
- **L3+C Physics:**
  - Atmospheric muon spectrum
  - Antiprotons at 1 TeV
  - A new flaring source ?
  - GRBs
  - Solar flare signals
  - Solar anisotropy
  - Primary composition in the knee region
  - Very forward physics
  - Exotic events
  - Meteorological effects.

The L3 experiment

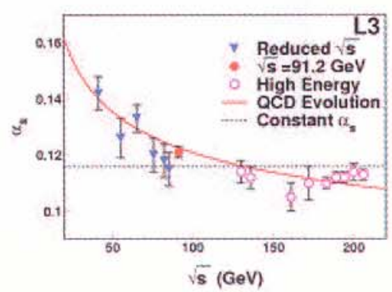
- Detector:
  - At LEP, CERN
  - Magnet, high precision drift chambers, calorimeters, vertex dectectors.
- Physics: "Standard model" and beyond

Electro-Weak Interactions (Unification)
Z- and W- bosons
Higgs-boson search
QCD Interactions
Running coupling "constants"
3 families of elementary particles
Search for heavy leptons, leptoquarks, SUSY
Extra dimensions (Graviton exchange)

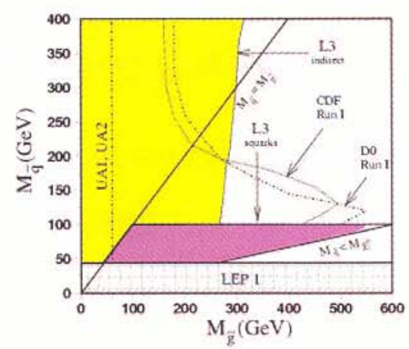




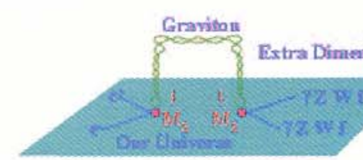
← EW



QCD



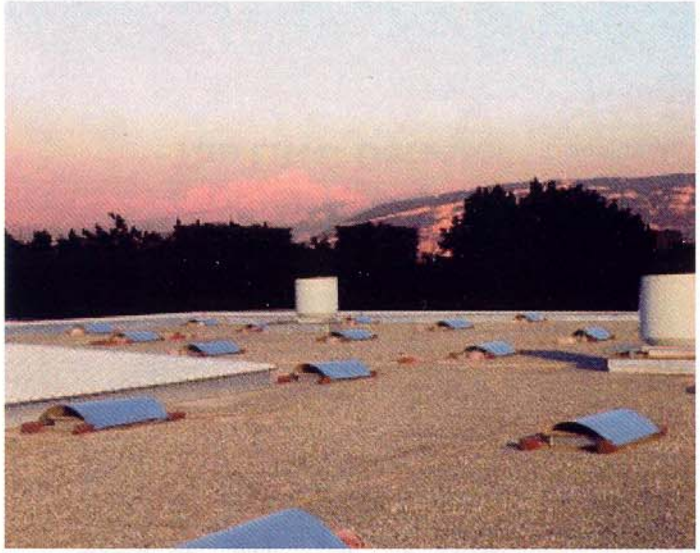
SUSY

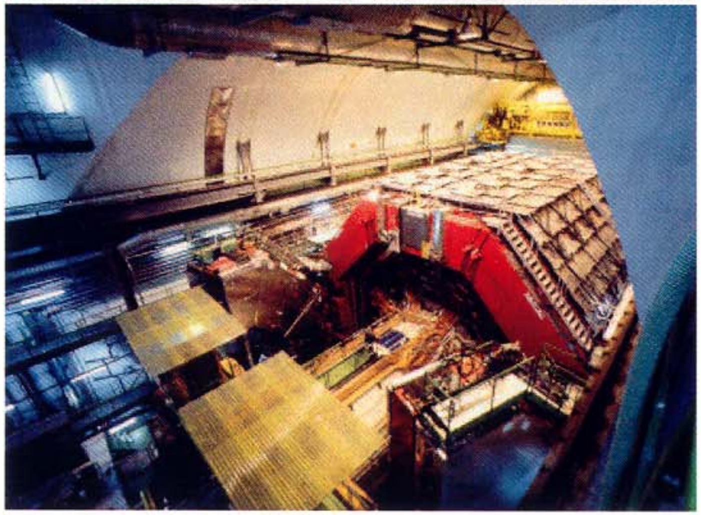


QG

The L3+C experiment

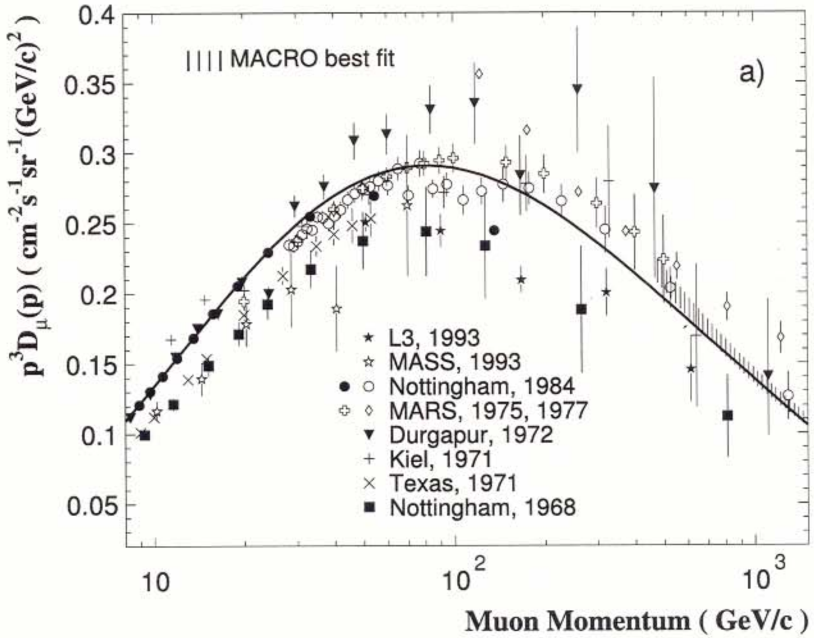
- Location: 6.02°E, 46.25°N, 450 m, LEP-CERN
- Muon Detector:
  - 30 m underground
  - Magnet (0.5 Tesla, 1000 m^3)
  - High precision drift chambers
  - T_0 detector (202 m^2 of scint.s, 1.8 ns res.)
  - GPS timing: 1 μs
  - Trigger and DAQ: independent of L3
  - Geom. acceptance: $\Sigma \cdot \Omega \simeq 200\,\mathrm{m^2sr}$
  - Energy threshold: $E_\mu > 15\,\mathrm{GeV}$
  - Mom. resol.: $\Delta\mathrm{p}/\mathrm{p}$ = 7.6 % at 100 GeV/c
  - Ang. resol.: $\delta\theta$ $<$ 3.5 mrad above 100 GeV/c
- Air shower detector:
  - 50 scintillators, S = $30 \times 54\,\mathrm{m^2}$
- Muon data: 1999-2000
  - $1.2 \cdot 10^{10}$ triggers, 12 TB data
  - 312 days live-time





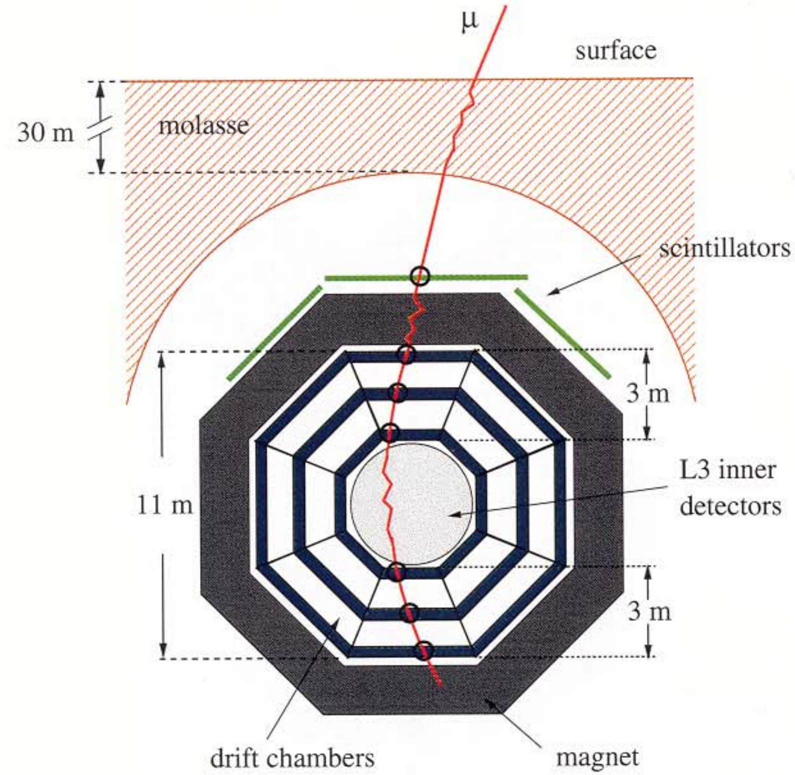
The muon spectrum in 1993 and the proposed spectrometer

Experimental data on atmospheric muons - the situation at start of L3+C



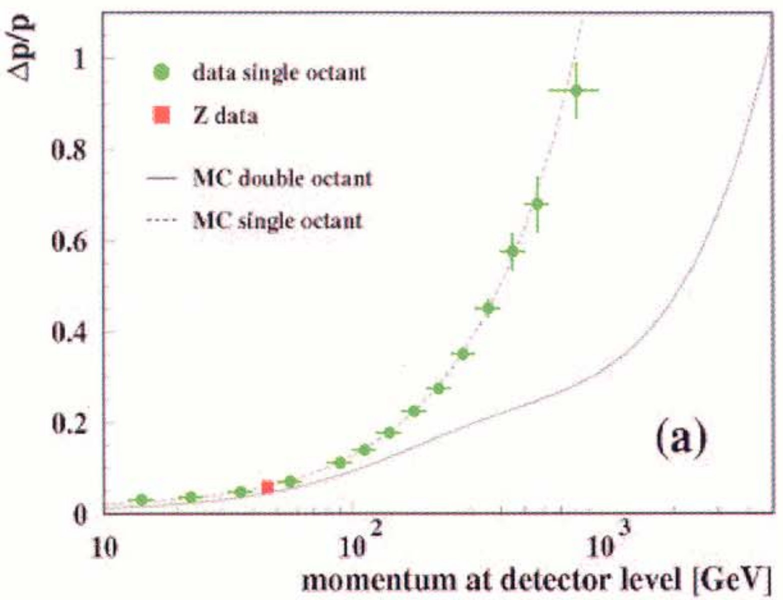
Compilation by E. Bugaev et al.,

Proc. 3rd NESTOR workshop, Pylos 1993



The L3+C Detector

The momentum measurement, resolution, efficiencies, acceptance



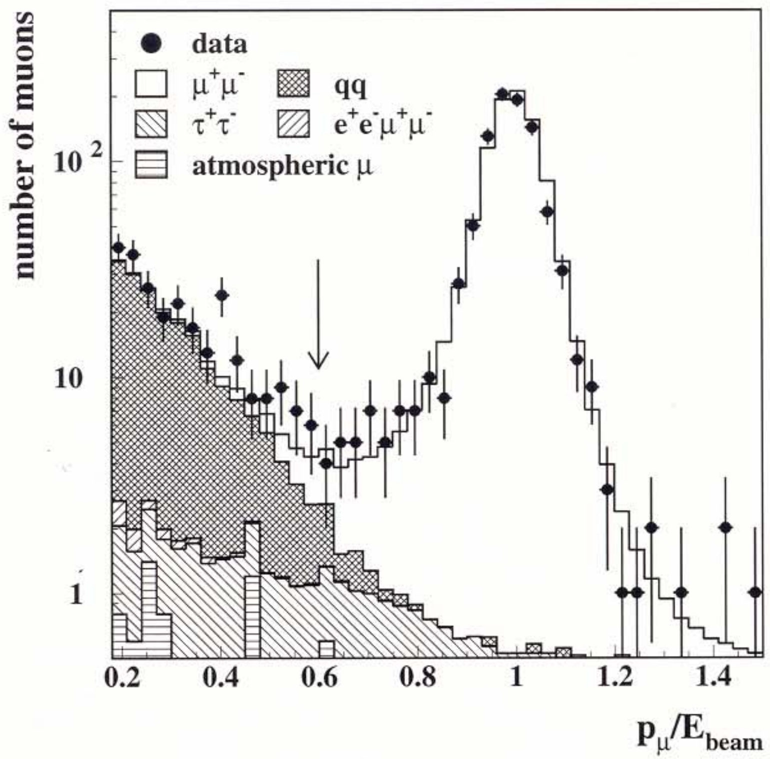
Momentum resolution at detector level

(Track position measured in 6 layers

(2 octants) in bending plane

and 4 positions in the non-bending plane.

→ excellent momentum resolution.)



Distrib. of p_μ / E_{beam} of Z-events and background.

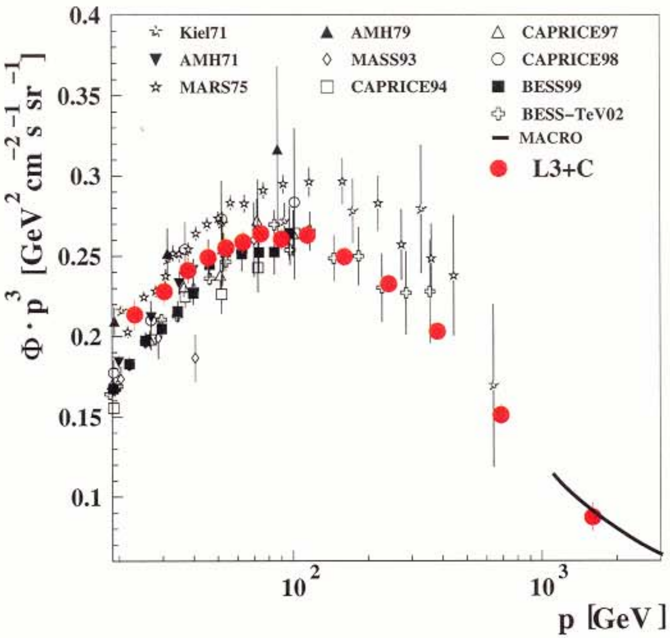
MC normalized to Standard Model.

(Unique for L3+C: Check of acceptance

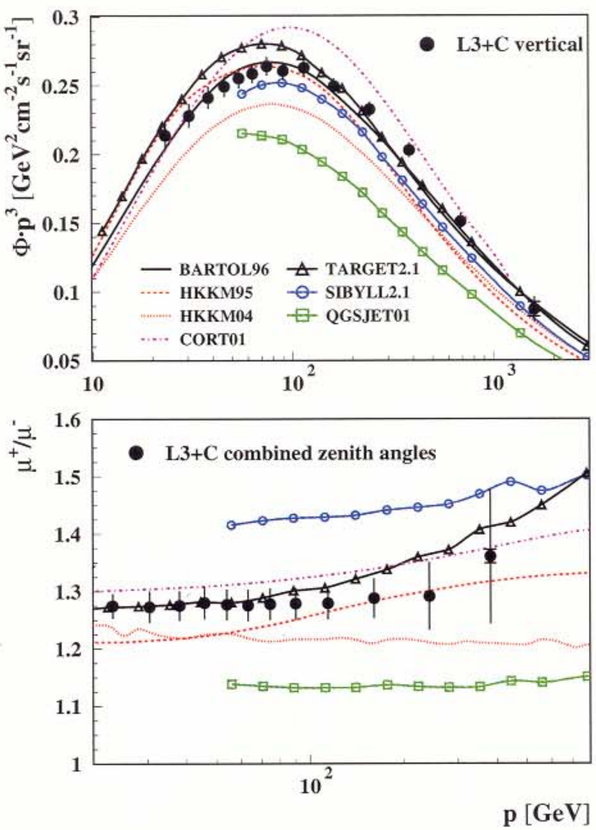
calculation and normalization with

$e^+ e^- \rightarrow Z \rightarrow \mu^+ \mu^-$ events.)

The muon momentum spectrum, results and comparisons

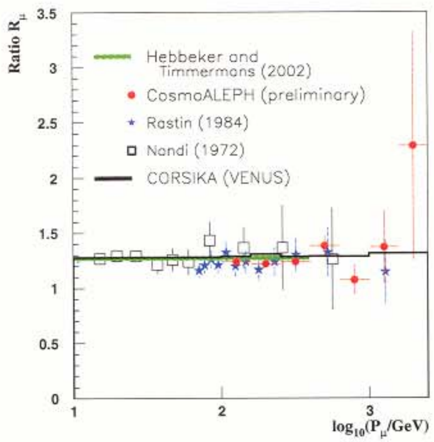


L3+C vertical muon spectrum at sea level compared to previous measurements providing an absolute flux normalization.



Calculated spectrum and charge ratio with different interaction models and given primary spectra.

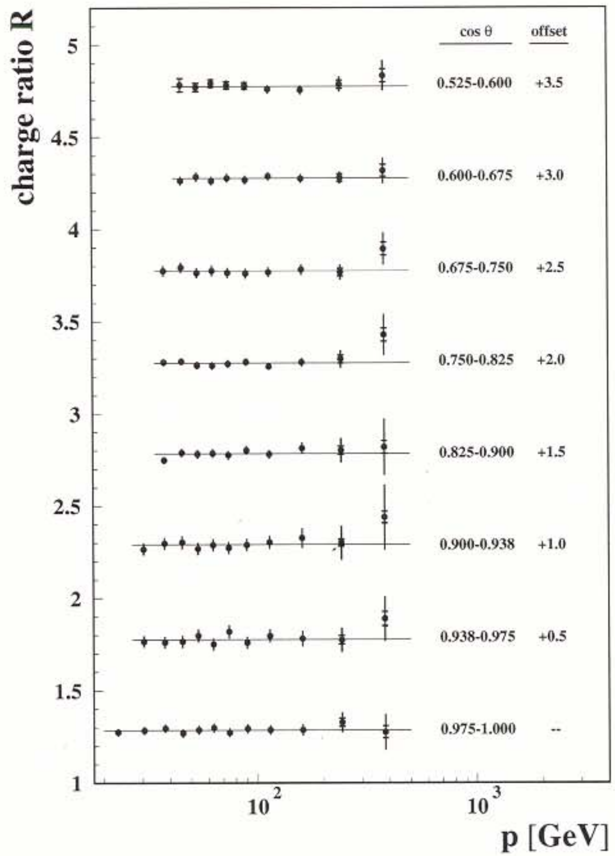
Muon spectrum: Charge ratio and angular dependence:

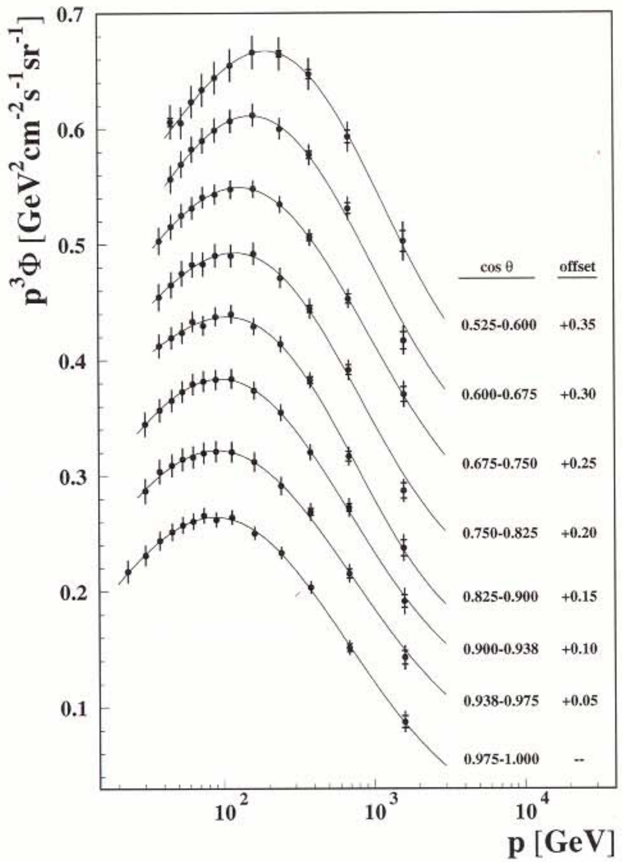


CosmoAleph:

Measured charge ratio.

Preliminary !



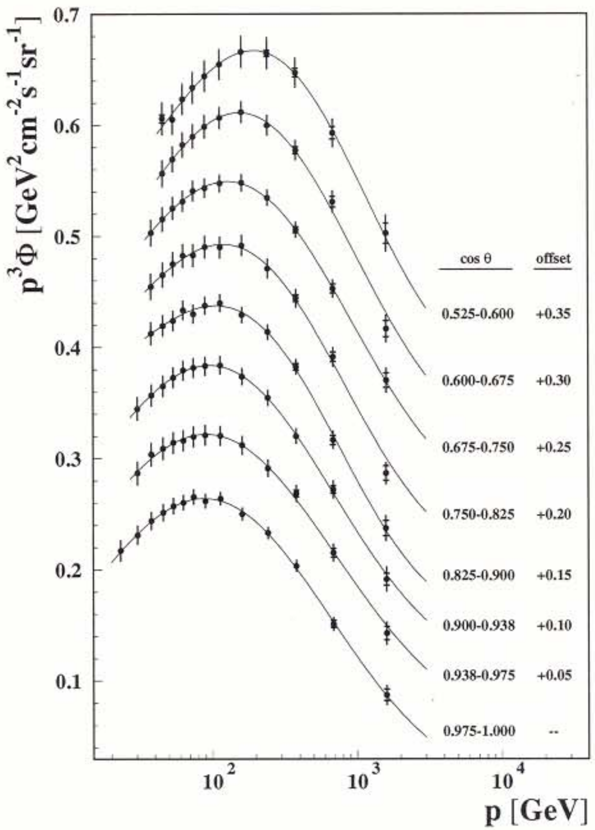


L3+C: Measured charge ratio for zenith angles ranging from 0° to 58° at 450 m above sea level.

$$\frac{\mu^+}{\mu^-}\Big|_{\text{vert.}} = 1.285 \pm 0.003(\text{stat.}) \pm 0.019(\text{syst.})$$

L3+C: Measured muon flux for zenith angles ranging from 0° to 58° at 450 m above sea level. Inner error bar denote statistical, full bars total uncertainty.

Muon spectrum, conclusions, motivations



Measured **muon flux** for zenith angles ranging from 0° to 58° at 450 m above sea level. Inner error bars denote statistical, full bars total uncertainty.

Conclusions:

- For given primary composition and flux the **parameters of interaction models** may be better constrained.
- The calculated atm. muon neutrino flux will b further constrained (**neutrino oscillation**).
- A good knowledge of the background ν_μ-, $\overline{\nu}$ flux is obtained for **neutrino astronomy** experiments.

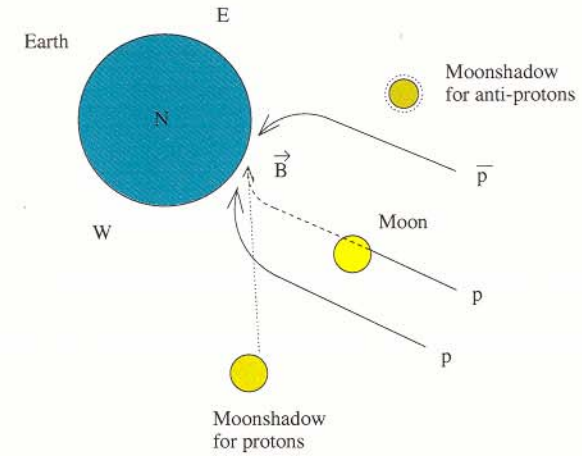
Publication: *Pys. Lett.* **B598** (2004) 15

Search for Antiprotons - The Earth-Moon system as a spectrometer

Cosmic rays are blocked by the Moon.

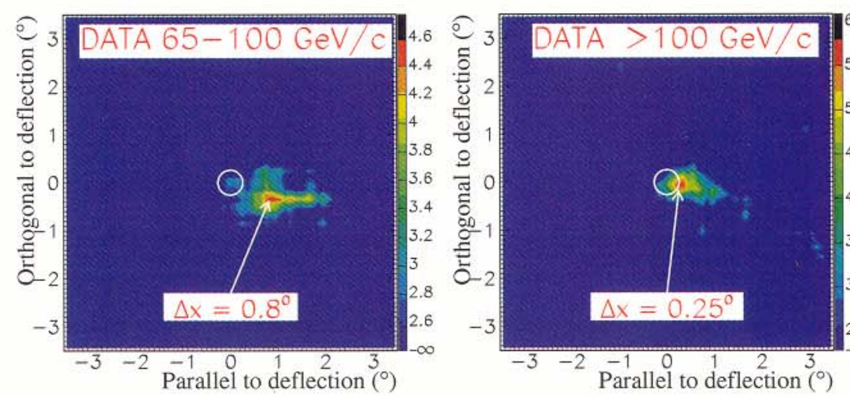
$\Longrightarrow$ deficit of cosmic rays when looking at the Moon (Clark 1957).

- Size of the deficit $\rightarrow$ effective angular resolution
- Position of the deficit $\rightarrow$ pointing error



Geomagnetic field: positively charged particles deflected towards the East and negatively charged particles towards the West. $\Longrightarrow$ ion spectrometer

- **Advantage of L3+C:**
  - Excellent angular resolution: $(0.22 \pm 0.04)^\circ$ for $p_\mu > 100$ GeV
  - Excellent pointing precision: $< 0.2^\circ$
  - Precise momentum measurement: $\Delta p_\mu / p_\mu = 7\%$ at 100 GeV
  - Low $p_{\mu,min}$ (high rate, large deflection)
  - Real sensitivity on the earth magnetic field.

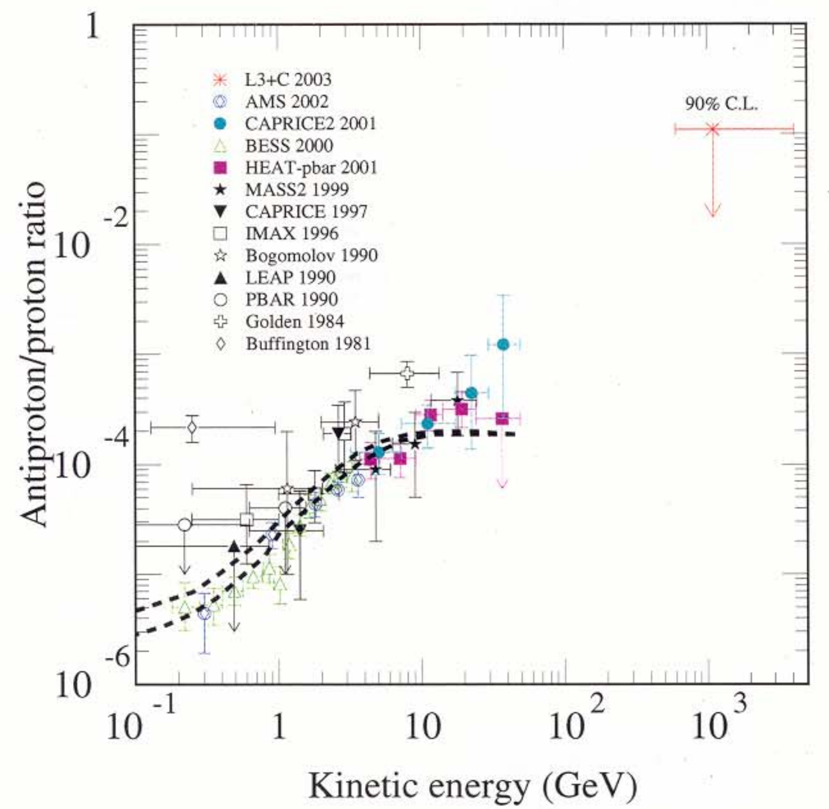


Shadow (in deflection coord. system; dipole field)

Antiprotons in space - L3+C flux limit around $E_{\overline{p}}$ = 1 TeV

- $\overline{p}$ (and e^+) in space provide information about the origin, the propagation and the nature of cosmic rays (CR).
- Theoretical models
  - Secondary production: Most CR $\overline{p}$ observed near Earth are secondaries produced in collisions of energetic CR particles with interstellar gas.
  - Exotic sources
    - Dark matter neutralino annihilation
    - Primordial black hole (PBH) evaporation ?
    - High energy antiprotons from extragalactic sources ??
- Measurements
  - Direct measurement: Balloon or satellite ($\overline{p}/p$ for $E < 50$ GeV/c)
  - Indirect method: Moon shadow:
    - EAS (CYGNUS, CASA, Tibet), Cherenkov (Artemis, CLUE), H_2O-Cherenkov (MILAGRO), Underground-μ (MACRO, SOUDAN) $\rightarrow$ No $\overline{p}/p$ limit up to now
    - L3+C: sensitive to field; gets a limit
  - Cosmic ray μ^+/μ^- ratio: model dependent; primary composition ?

Data:



(Adapted from Boezio, M., et al., 2001, ApJ, 561, 787)

L3+C around 1 TeV: $\overline{p}/p < 0.11$ **(90%CL)**

Publication: *Astropart.Phys.* **23** (2005) 411

Search for signals from point sources with LEP detectors

Difficulties:

⇒ γ - induced showers produce less muons than proton induced ones.

⇒ According to existing measurements: LEP detectors have no chance to observe a steady signal.

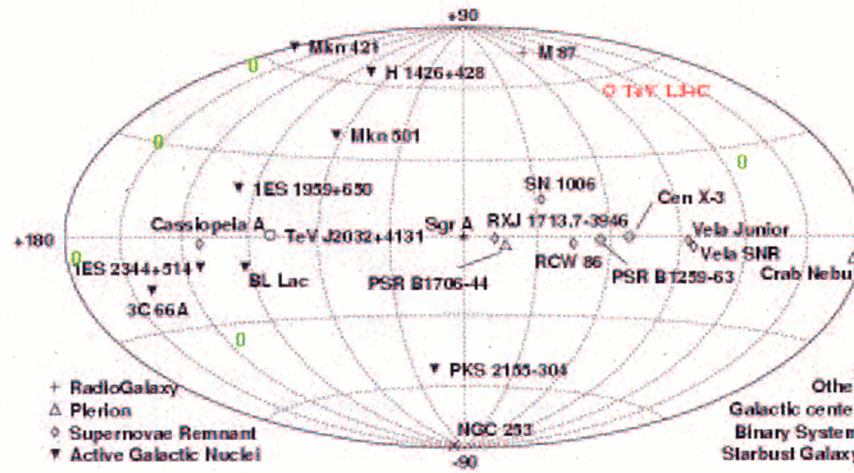
BUT: Flare signals (Blazars, AGN, ?) or Gamma Ray Bursts (GRB) may be observed.

The experimental advantages are manyfold:

- "Full" sky survey (Zenith angle: 0^o to 60^o)
- Continuous acquisition
- Low muon threshold ($E_\mu \geq$20 GeV, $E_\gamma > 200$ GeV)
- Selection of the $E_\mu^{Thr.}$ off-line (optimisation of the signal to background ratio)
- The background is continuously monitored
- Sources followed accross the sky
- Good $\angle$ - resolution (e.g. L3+C: $< 0.22^o$ for $E_\mu > 100$ GeV)
- Excellent pointing accuracy (better than 0.1°)
- Geometrical acceptance of order 100 $m^2 sr$.

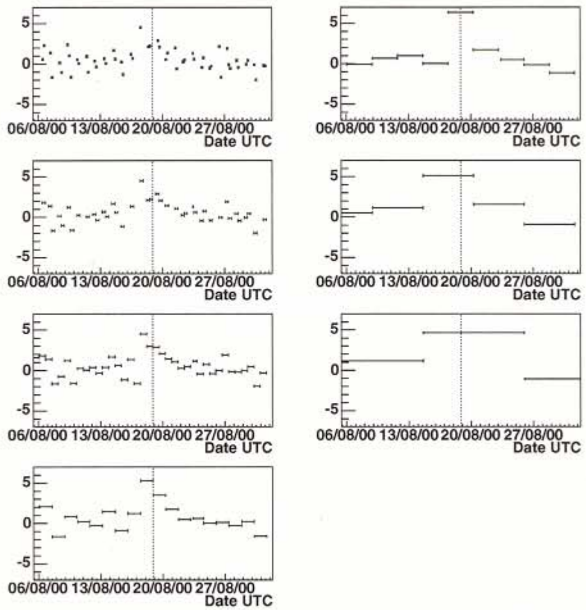
Results:

T.C. Weekes, 2003, TeV so



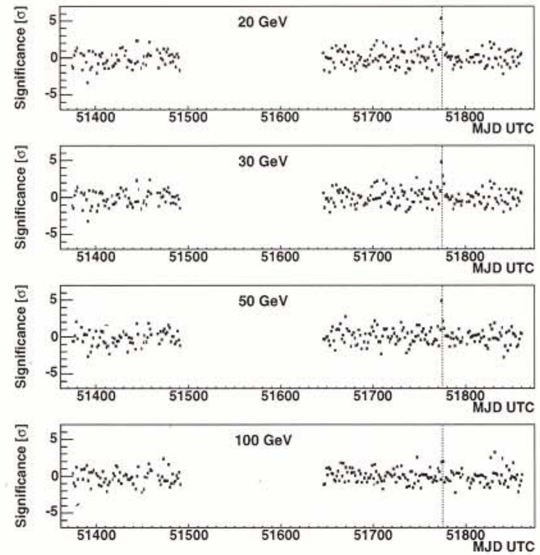
- **Cosmo-ALEPH:** Direction of muon bundles wi $n_\mu > 75$ (O) [*Astropart.Phys.***10**(2003) 513] No pointing to a known TeV γ-source.
- **L3+C:** One flare possibly observed (O). See oral presentation (OG 2.3).

Characteristic features of the signal



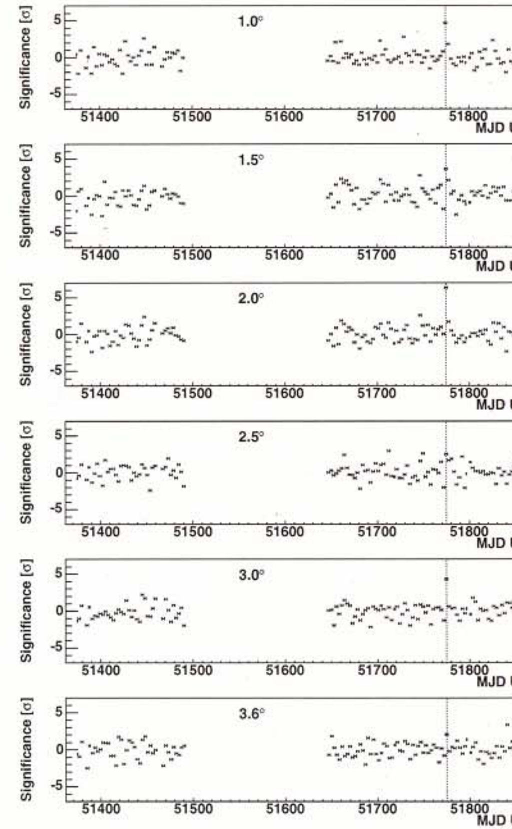
The time evolution

Time windows ranging from 2^8 min to 2^{14} min.



The energy dependence

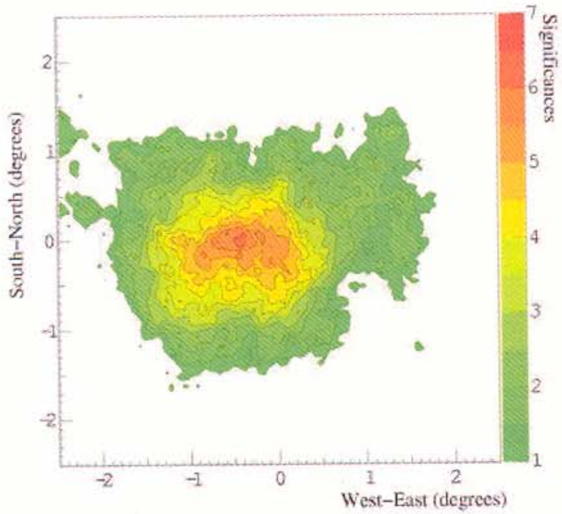
Muon energy thresholds = 20, 30, 50 and 100 GeV (time bin = 2^{12} min).

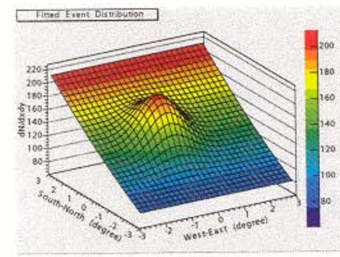


The cell size dependence

Cell-sizes = $(1.0^\circ)^2$, $(1.5^\circ)^2$ $(2.0^\circ)^2$, $(2.5^\circ)^2$, $(3.0^\circ)^2$.

Two dimensional analysis of the possible flare





MAGIC telescope, La Palm

Fit results:

- Position:

  Right ascension: α = $(172.53 \pm 0.17)^\circ$

  or: α = 11h30m07.2s

  Declination: δ = $(-1.19 \pm 0.17)^\circ$

  Galactic longitude = $(265.02 \pm 0.42)^\circ$

  Galactic latitude = $(55.58 \pm 0.25)^\circ$

- Angular resolution: $(0.70 \pm 0.13)^\circ$

Estimated gamma flux values:

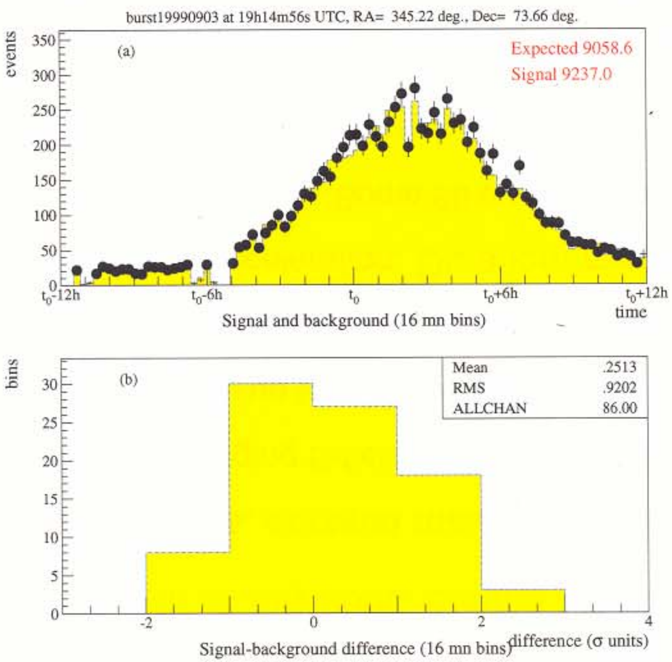
Assumed differential flare spectrum: $I_\gamma \sim E^{-\gamma}$

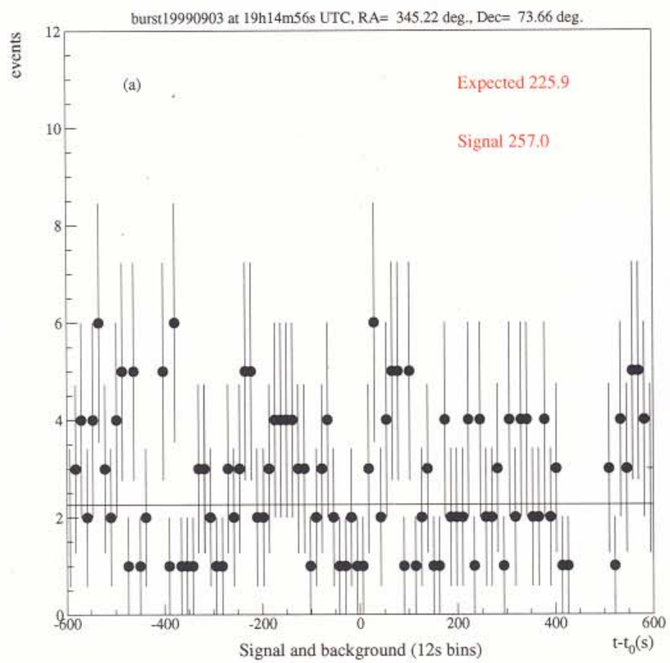
Flux-Units = 1 Crab (= $1.8 \cdot 10^{-11}$, $5.3 \cdot 10^{-13}$, $9.9 \cdot 10^{-14}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, for $E_\gamma > 1, 10, 30$ TeV.)

Slope	I(>1 TeV) [Crab]	I(>10 TeV) [Crab]	I(>30 TeV) [Crab]
-2.5	$2.2 \cdot 10^4$	$2.9 \cdot 10^4$	$3.3 \cdot 10^4$
-3.5	$4.0 \cdot 10^3$	$5.2 \cdot 10^2$	$2.0 \cdot 10^2$
-4.5	$3.5 \cdot 10^2$	$4.6 \cdot 10^0$	$5.9 \cdot 10^{-1}$

Search for Gamma ray burst signals:

- 8 GRBs analyzed: GRB 990903, 990917, 991025, 991103, 991106, 000403, 000415, 000424
- No signal ($E_\mu > 20$ GeV) found: within 10 sec following the GRB time, in a 1 hour window around the GRB time, and within a 24 hour window.
- Figures below: Signal (dots) and background (yellow) muon rate from GRB 990903 using 16 minute binning (left, upper), standard deviations (left, lower : data-background), and 12 sec binning (right).

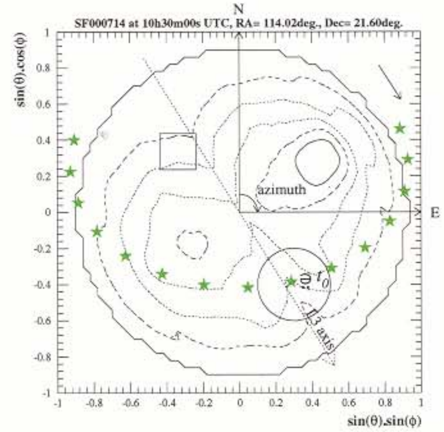


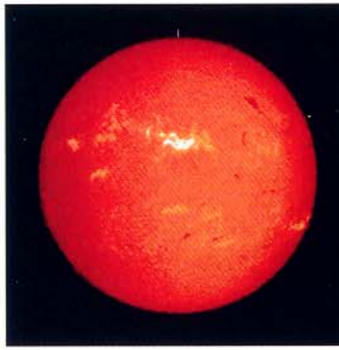


Solar flare of the 14th of July 2000

Question: May protons be accelerated to more than 40 GeV in solar flares ?

- On the 14th of July 2000, around 10h30 UT, the sun was almost overhead in Geneva.





- **Solar flares, coronal mass ejections:**

  Rapidly changing B-fields → electrical fields:

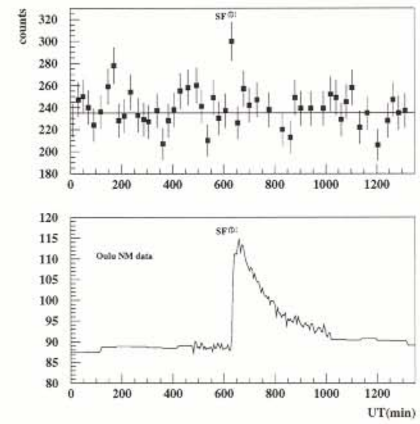
  Accelerations up to 13 GeV (determined by local geomagnetic rigidity - Huancayo neutron monitors).

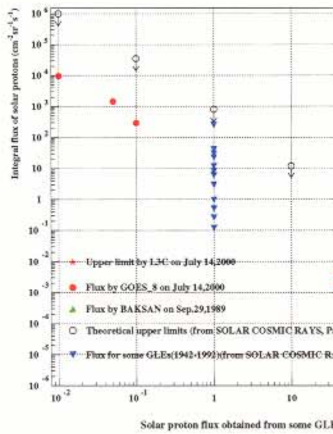
  Also shock acceleration. Duration: minutes to hours

  Rare occurences:Some 60 events since 1946, preferentially at Solar max. Spectrum: steep.

- **L3+C observation:** Between 10h24 and 10h42 UT (flare time) 65 muons (E_μ=15-25 GeV) were found in excess of a background of 235 in a particular sky cell (see Fig.). The prob. for this excess to be a b.g. fluctuation is 1 % (41 cells).

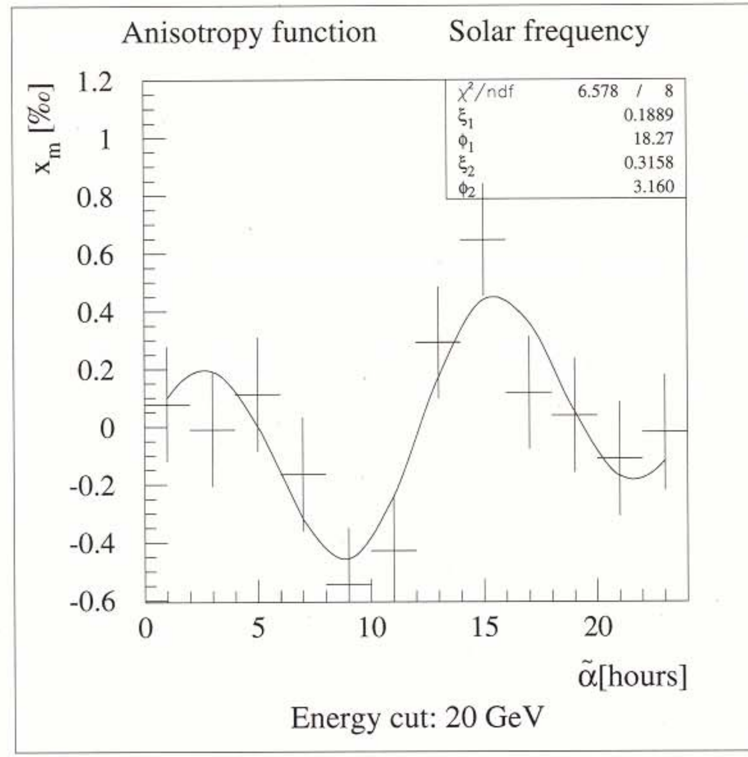
  $I(E_p \geq 40 GeV) \leq 2.8 \cdot 10^{-3}/(cm^2 s\, sr)$, assuming an E_p^{-6} spectrum.

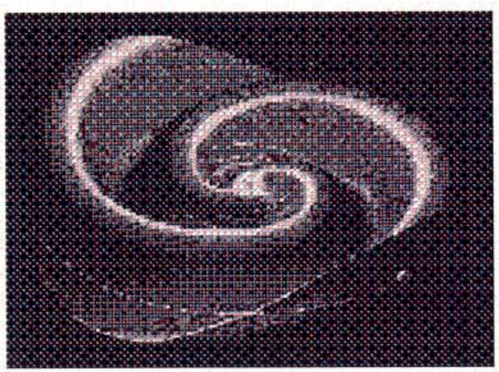




Directional anisotropies in the primary flux:

- L3+C's sensitivity to the anisotropy of the arrival direction of primaries is 10^{-4}.
- No deviation from isotropy is observed at the sideral frequency for any of the first 3 harmonics.
- For muons above 20 or 30 GeV (primary protons $\sim$ 250 GeV) a significant departure from isotropy has been found for the 2nd harmonics at Solar frequency (see Figure). The stucture found is similar in shape to the result of the GRAND experiment at 0.1 GeV threshold, but with smaller amplitude.



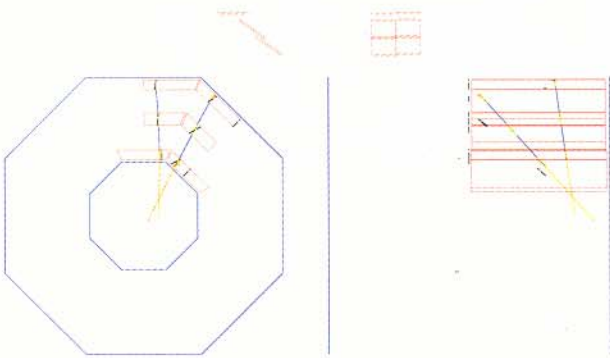


Data collection: Mid July - November 1999, and April - November 2000.

Ref.: R.Ramelli, phD. thesis: No. 14683, ETH, 2002

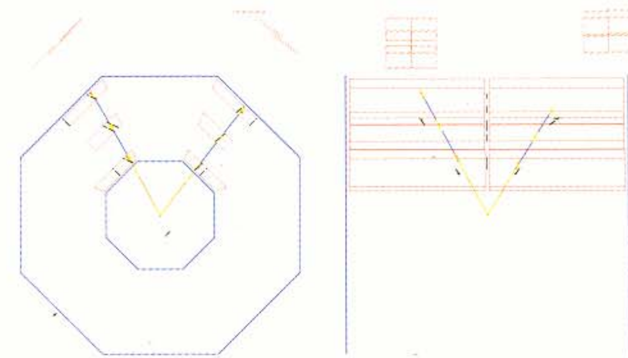
Exotic events:

Motivation: - Kolar Gold field events: 5 two- and three- prong events, vertex in air, large opening angles, probably decays of unknown particle. - Yunnan event: 3 collimated tracks with vertex in target, one slow heavy particle with large momentum, probably interacting unknown heavy particle. - : L3+C has large volume and precise momentum measurement ! $\Rightarrow$ **Dark Matter, SUSY particles ??**



A candidate event ?

- L3+C: To-day's sample: $1/4$ of all $1.2 \cdot 10^{10}$ events.
  Filters reduced this number.
  Rest = $1.4 \cdot 10^5$ events scanned by eye.
  No candidate survived all criteria.
- Upper flux limit for 2 prong exotics:
  $7.1 \cdot 10^{-13}\ cm^{-2} s^{-1} sr^{-1}$
  Preliminary!
- 3-prong event search in progress.



$$e^+ e^- \rightarrow W^+ W^- \rightarrow \mu^+ \mu^- \nu_\mu \overline{\nu_\mu}$$

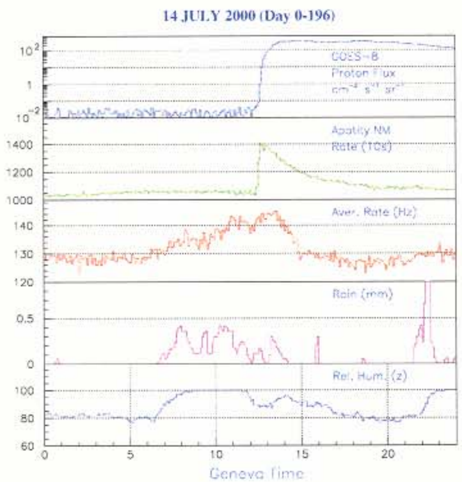
- LEP events found = allows checking filter and scan efficiency.
- Expected number of $WW \rightarrow \mu\,\mu\,\nu\,\nu$ events = 1.5
- Observed: 1 event

Environmental and meteorological effects:

Low enery Solar flare signals seen with the surface scintillator array ?:

L3+C is presently searching for a possible flare signal detected by the surface scintillator array.

But meteorological effects have first to be fully understood.



Detector responses as fct. of time. Top to bottom:

- Satellite (GOES-8) record of proton flux (large increase at time of flare);
- Neutron monitor data (Apatiti);
- L3+C EAS detector record;
- Rainfall + Humidity (at GV airport)

- **L3+C Observation:** Increased single EAS detector rates start ≈ 3 before Solar flare (due to rain). But Max. obse time of flare (due to flare ??) (still under investigation).

- **Interesting questions:** - Precipitation of aero containing radio nuclides continue for hours, w How are radio nuclides continually replenishe Do CR-particles play a significant role in produ radio nuclides ? Does the CR-particle flux pro ions suitable for condensation and drop forma Variation of CR-particle flux (caused by intera the Solar wind with the geomagnetic field) imp for enhancing condensation and precipitation suitable atmospheric conditions ?

CONCLUSIONS:

- Final results of the measurement of the vertical atm. muon momentum spectrum together with the zenith angle dependence and the charge ratio.
- A limit on the $\overline{p}/p$ ratio around 1 TeV from the observation of the (energy dependent) Moon shadow.
- Upper flux limits for point source signals of one day, or months duration, for 4 different $E_\mu^{thr.}$ (sky survey). Also for 10 selected sources.
- One Blazar flare possibly observed.
- No signal from 8 selected GRB has been found in 10 sec, 1h, or 1d time windows.
- An upper flux limit of protons with $E_p > 40$ GeV from the 14 July 2000 Solar flare could be given.
- The Solar anisotropy has been observed for 200 GeV protons.
- Analysis still in progress on several other topics: Search for exotic events, Primary composition in the knee region, very forward physics, Meteorological effects.