29th International Cosmic Ray Conference Pune (2005) **10**, 137–150

# Cosmic Ray Observations and Results from Experiments Using LEP Detectors at CERN

P. Le Coultre
*Institute of Particle Physics, ETH CH-8093 Zürich, Switzerland*
Pierre Le Coultre (Pierre.Le.Coultre@CERN.CH)

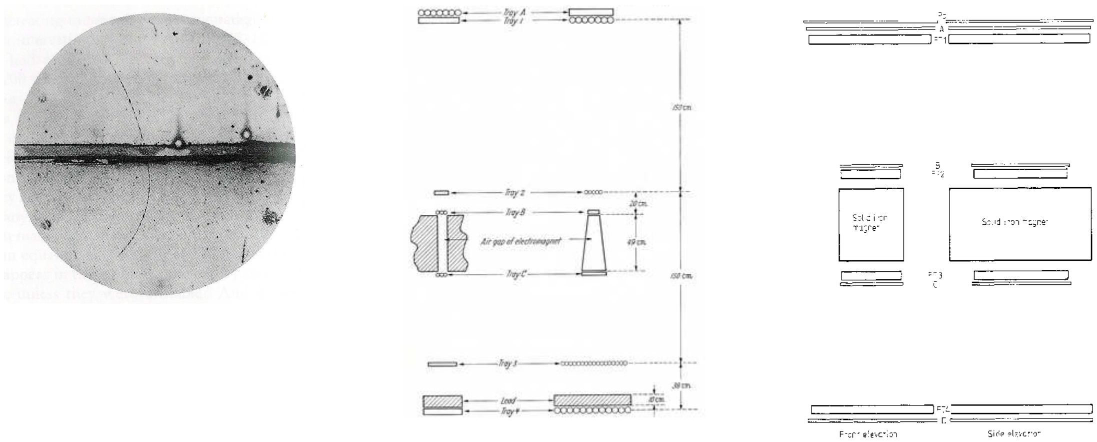
A short overview of results relevant for cosmic rays and astroparticle physics obtained with three LEP detectors at CERN, Geneva, is presented.

## 1. Introduction

LEP activities have stopped end 2000. Therefore all measurements have been done already nearly 5 years ago, and most results are probably known. Nevertheless, some data analysis is still on-going and many results have not yet been published. LEP being located underground means, obviously, that we are discussing essentially about high energy cosmic ray muon physics.
This presentation consists of a short historical overview of muon detection, on precision spectrometers, and the cosmic ray topics studied at LEP.

## 2. Short historical remark

In 1900, while measuring the conductivity of air, C.T.R.Wilson's made his famous remark that "there must exist an extraterrestrial radiation which is responsible for discharging my electroscope". This triggered a lot of investigations... It was Skobeltzyn who first used a Wilson cloud chamber in a magnetic field as a spectrometer for studying the new unknown radiation [1]. In 1932 C.D.Anderson discovered the positron [2] (Figure 1a), which represents the first particle discovery in cosmic rays, and the second, the muon, was also found with this technique five years later [3].
Measurements of the muon spectrum started immediately and a compilation of data was given by Rossi in 1948 [4]. The first pure counter muon spectrometer was built in Melbourne by Caro et al. in 1950 (Figure 1b), establishing a muon spectrum up to 53 GeV/c [5]. The Manchester spectrograph [6] consisted of two magnets, with 6 layers of counters, and a spectrum between 0.5 and 20 GeV/c was published [7]. Adding cloud chambers to the Manchester spectrograph allowed Rodgers [8] to get a spectrum up to 1 TeV [9]. In 1984 B.C.Rastin published the Nottingham spectrometer data, a muon spectrum ranging from 4 to 3000 GeV [10] (Figure 1 c). Many other spectrometers were built [11], but most of the high energy ones are based on $dE/dx$ and range measurements [12, 13, 14]. The main reason for this choice is the high costs of strong field magnets with large acceptance and precision tracking detectors. For references about newer measurements see e.g. [15, 16].
In more recent times very large particle physics detectors were built at accelerators and colliders and this obviously triggered the idea to use them also for cosmic ray experiments (UA1 at the $Sp\bar{p}S$, CERN, among others).

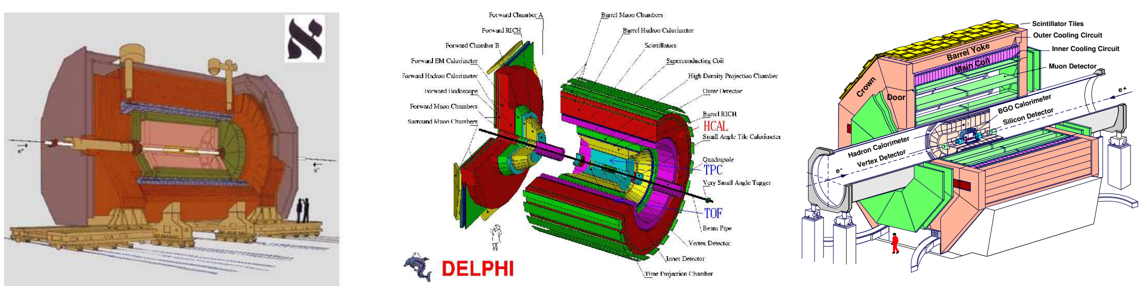



(a) (b) (c)

**Figure 1.** a.) Cloud chamber with magnetic field (Anderson's positron). b.) The Melbourne spectrograph. First pure counter spectrometer: Geiger tubes and air gap magnet (Caro's set-up). c.) The Nottingham spectrometer: magnetized iron and Geiger tubes (Rastin spectrum).

## 3. New opportunities

At LEP three detectors have been used for cosmic ray studies (see Figure 2):

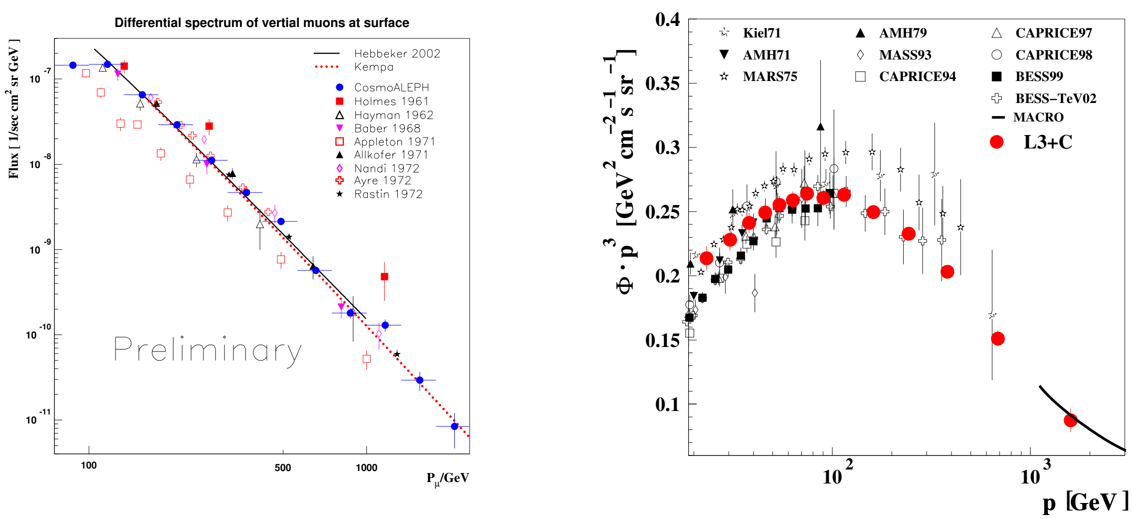



(a) (b) (c)

**Figure 2.** a.) ALEPH b.) DELPHI c.) L3+C

ALEPH: It is located 130 m below ground and has therefore a muon threshold of 70 GeV. Data of the TPC, as well as of the hadron calorimeter, have been analyzed. Five scintillator stations were installed along the beam line, in order to record also associated particles, to study the lateral distribution. The physics topics concern

mainly the muon multiplicity.
This is also the case for DELPHI, which is located at a depth of 100m, with a muon threshold of 50 GeV. The hadron calorimeter, the TPC and the TOF system were used.
L3+C has been proposed in 1987 and became a "recognized experiment" (RE4) at CERN in 1998 [17]. It was located under 30 m of molasse, corresponding to a muon energy threshold of 15 GeV. The high precision drift chambers were used, together with extra installed timing scintillators and an L3 independent trigger and Data Acquisition system (DAQ). On the roof of the surface building a small air shower scintillator array has been installed. Many different physics topics are being studied, in particular a precision muon spectrum was obtained.
The advantages of these detectors over previous spectrometers are the large acceptance, the precision of the muon momentum measurement and the excellent understanding of the detector properties through very accurate Monte Carlo simulations and the experience gained with the $e^+ e^-$ physics. LEP events could be used to check the detection efficiency and the momentum measurement in L3+C, e.g.
An experimental limitation is given by the fact that such large devices can only be run in parallel with LEP, because of the important manpower needed and the costs of the magnet power.



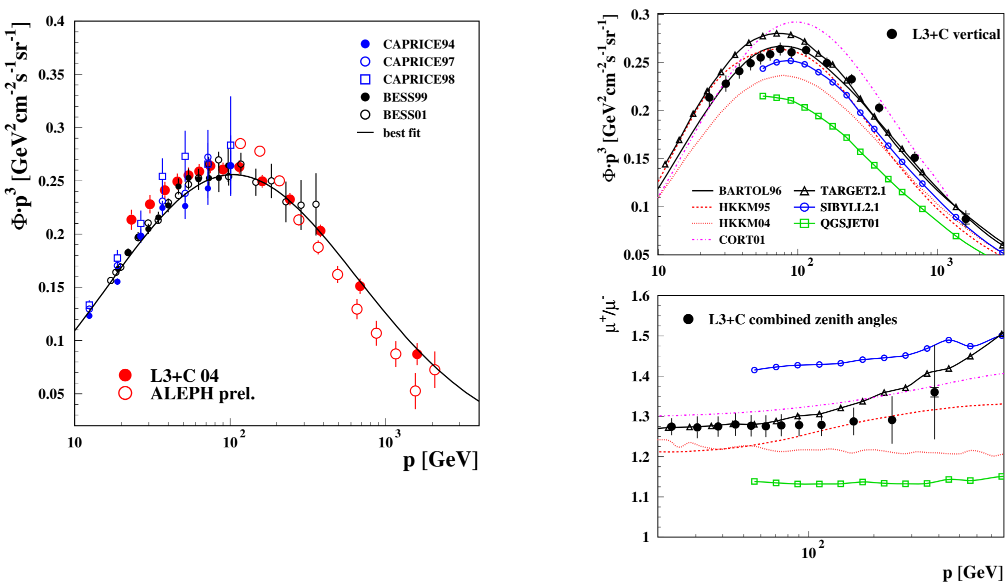

(a) (b)

**Figure 3.** a.) ALEPH's preliminary spectrum (normalization to reference [16]; only statistical uncertainties) and comparison to previous measurements. b.) L3+C absolute spectrum [19] compared to previous measurements providing absolute flux results (sea level data) [20, 21, 22, 23, 24, 25, 26].

## 4. The muon momentum spectrum:

The first physics topic to be discussed concerns the measurement of the atmospheric muon momentum spectrum between 20 and 3000 GeV. Figure 3a.) shows preliminary results obtained by CosmoALEPH about the vertical, differential muon spectrum (full dots) [18]. No normalization is yet available and the unfolding is not yet applied. Their spectrum is "normalized" here to the estimated best average spectrum calculated by Hebbeker and Timmermans in 2002 based on measurements giving absolute flux values [16]. The error bars give the statistical uncertainty. The comparison is made with older measurements.

In Figure 3b.) the final and published L3+C result is shown [19]; but here the flux is multiplied with the 3rd power of the momentum in order to see details along the steep spectrum. The data range from 20 to 3000 GeV, the total error at 150 GeV amounts to 2.4 %. A comparison is made here only with experiments providing an absolute flux normalization. Best agreement is obtained with BESS [20], from 50 GeV up to 300 GeV. CAPRICE [21] agrees also with their measurements ranging up to 100 GeV. Kiel [22] agrees in shape, but records a systematically higher flux, while MARS [23] disagrees in shape and absolute flux. MACRO [24] agrees at the high energy end of the spectrum.

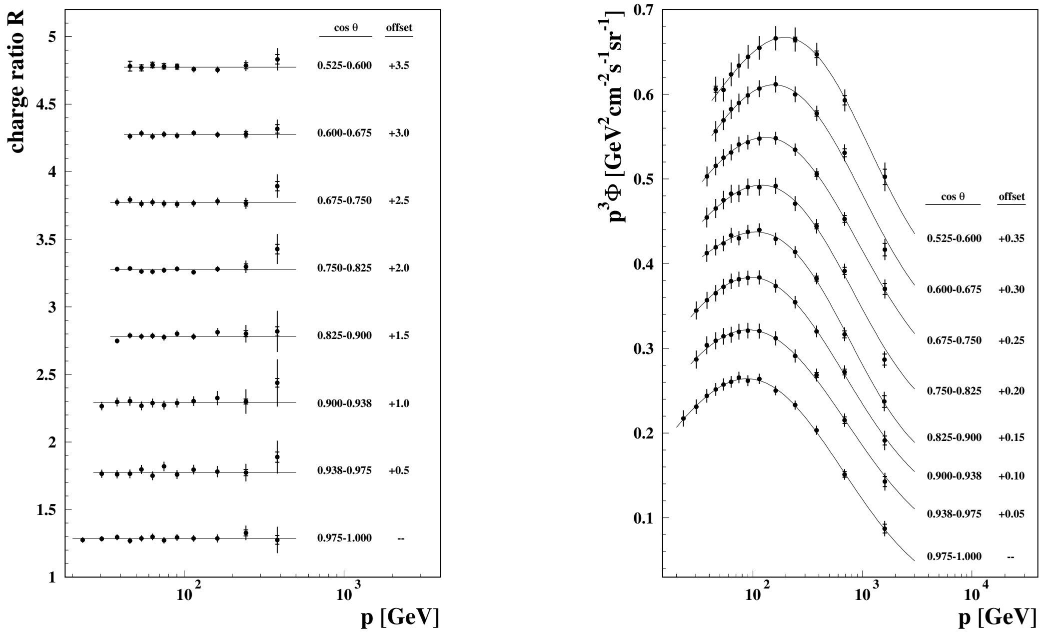



(a) (b)

**Figure 4.** a.) Most recent measurements including a fit (curve). The preliminary ALEPH data are excluded from the fit. b.) Comparison of the L3+C spectrum with cascade calculations using different interaction models and primay spectra (see text).

In Figure 4 a.) a comparison is made again with the most recent measurements: A fit of BESS, CAPRICE and L3+C data, with the phenomenological function used in [15,16] gives a $\chi^2$/Ndf=1.2 taking into account the systematic momentum scale and normalization uncertainties quoted by the collaborations (the ALEPH data are excluded from the fit).

Figure 4 b.) shows a comparison between the L3+C vertical spectrum and results of cascade calculations using different interaction models [27]. Using pre- AMS/BESS primary spectra [28] the Fritjov (HKKM95, [29]) and Bartol 96 [30] models give best agreement. Larger discrepancies are observed using the upper primary flux parametrization of reference [29] with the transport program TARGET [31] and the different interaction models Target2.1 [33],QGSJET01 [34], SIBYLL2.1 [35]. Target2.1 gives the best approximation, whereas OGSJET01 shows the largest discrepancy. The HKKM04 [36] interaction model with the AMS/BESS primary spectrum delivers a muon spectrum with a normalization differing by 15 % from the L3+C data. See also the modified DPMJET-III model [37, 38] in these proceedings, FLUKA [39] and CORT [40].




(a) (b)

**Figure 5.** a.) L3+C: Charge ratio as a function of the zenith angle between $0°$ and $58°$. b.) The muon spectrum as a function of the zenith angle. The inner error bar corresponds to the statistical, the full error bar to the total uncertainty. All data are valid for 450 m above sea level.

L3+C [19] provided the charge ratio between 20 and 500 GeV, and got a final value of $1.285 \pm 0.003(\mathrm{stat.}) \pm 0.019(\mathrm{syst.})$ in this energy range for the vertical direction (see lower panel of Figure 4b.). Shown in Figure 5 a.) is the zenith angle dependence of this ratio for 8 different zenith angles ranging between $0°$ to $58°$.
The angular dependence of the spectrum (Figure 5 b.)) is also measured by L3+C between 20 and 3000 GeV. The inner error bars denote the statistical uncertainty and the full error bars the total uncertainty.

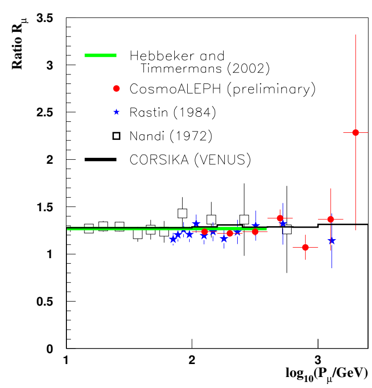
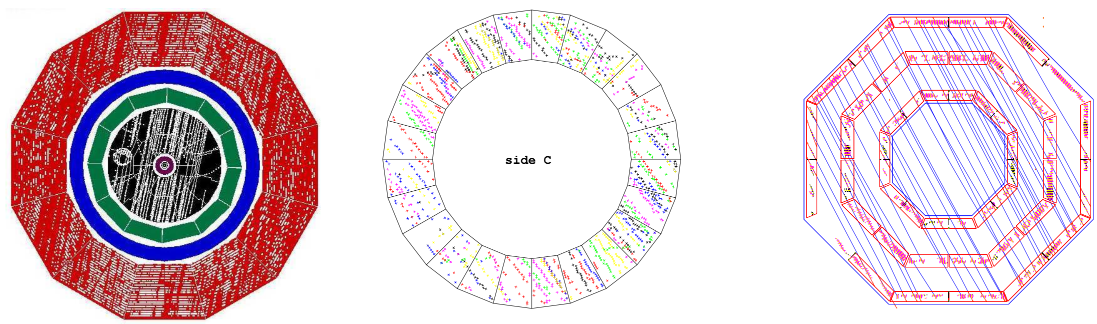



**Figure 6.** ALEPH's preliminary charge ratio for vertical incident muons.

ALEPH's preliminary charge ratio between 80 and 2500 GeV is plotted in Figure 6. A fit gives a constant value of $1.278 \pm 0.011(stat.)$ [18] and good agreement with L3+C is observed.

## 5. Multi-muon events:

All three LEP experiments are getting results about multi-muon events, or muon-bundles (Figure 7 a.,b.,c.). ALEPH used the TPC and the HCAL and got events with up to 150 parallel muons, DELPHI used mainly only the HCAL, got up to over 100 muons per event, and L3+C is presently analyzing multimuon data in coincidence with their air shower array observations.
The duty cycle is 17% for ALEPH, 18% for DELPHI and 100% for L3+C, thanks to their L3-independent DAQ.



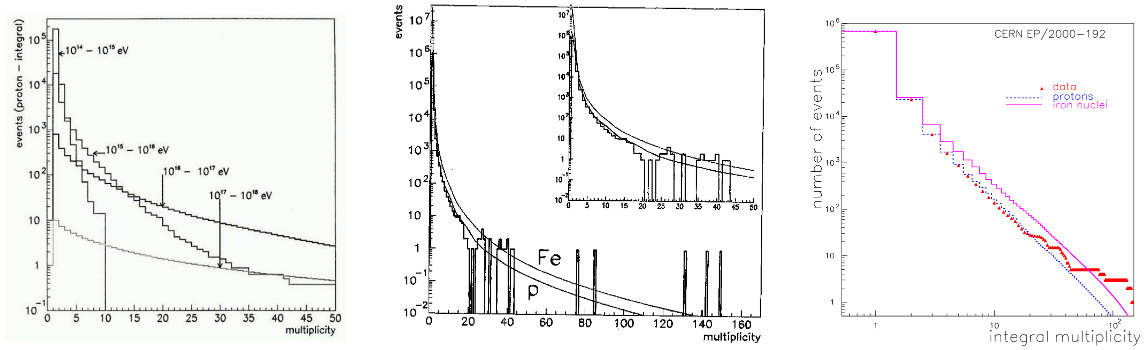

(a) (b) (b)

**Figure 7.** Example of multi-muon events. a.) ALEPH, b.) DELPHI, c.) L3+C.

Muons selected underground with energies $E_\mu \geq 100$ GeV originate from first ineractions at the top of the atmosphere and are therefore most sensitive probes of the primary composition and interactions at high energies. The concerned range of the primary spectrum runs from $10^{14}$ to $10^{16}$ eV/nucleus. The central muon multiplicity is expected to be larger for Fe than for p induced showers. Recording multi-muon events is therefore particularly well suited to detect new informations about the two mentioned topics.
Unfortunately the experimental difficulty with the kind of detectors we are talking about, is that only part of the shower can be detected; the total number of produced muons, the shower axis and the primary energy remain unknown. Even L3+C, with its air shower array, faces difficulties to estimate these quantities precisely, due to the relatively small effective size of the scintillator array.
The theoretical difficulty is the strong coupling between the topics to be studied (composition, type of interaction and very forward particle production).

### 5.1 ALEPH's results:

The data are compared to CORSIKA [41] air shower simulations with the QGSJET interaction model [42]. Two cases are distinguished: p and Fe primaries. According to the data at low recorded multiplicities, the protons are favoured over the Fe primaries, see Figure 8. Above a multiplicity of about 20 muons, the Fe as primary is favoured. At very large multiplicities the model fails to reproduce the observation and there exist even extraordinary large multiplicity events, which cannot be explained in the framework of current shower simulations.




(a) (b) (c)

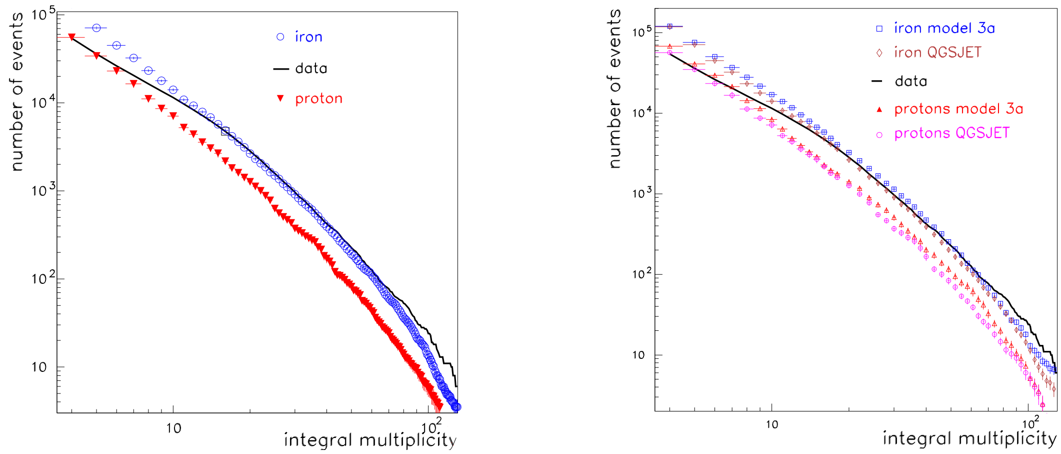
**Figure 8.** Cosmo-ALEPH a.) The contribution of different energy intervals of the primary spectrum to the integral muon multiplicity distribution for proton induced showers scattered over 200 × 200 $\mathrm{m}^2$. b.) Observed multiplicity distribution of muons in the TPC compared to CORSIKA simulation for primary protons and Iron nuclei, normalized to the effective running time. c.) Distribution of the observed integral muon multiplicity compared to CORSIKA predictions for primary protons and iron nuclei.

### 5.2 DELPHI's results:

DELPHI observes the same behaviour: a trend from lighter to heavier primaries [43]. Figure 9 shows the distribution of the integral muon multiplicity.
DELPHI's CORSIKA calculation ranges from $10^{12} - 10^{18}$ eV, and four different primary spectra are tested (see Figure 10). The QGSJET interaction model cannot reproduce the data correctly. Best adjustement is obtained with an unrealistically large primary flux (1). J. Hörandel's modifications of the proton-nucleus cross-section 3a [44] (Figure 9 b.) improves the agreement only partially. Using the fluxes labelled (2), (3), (1b) in Figure 10 increases the discrepancy with respect to the data. As marked in Figure 10 the main contribution to the data originates from the knee region of the spectrum.

### 5.3 L3+C:

L3+C is still analyzing data. It has several important advantages thanks to the surface air shower array and the momentum measurement of the individual muons in a lage magnetic volume (1000 $\mathrm{m}^3$).
Their aims are to get the absolute rate of multiple muon events, the multiplicity as a function of threshold momenta, and the momentum spectra of the individual muons in muon bundles. These data should also be analyzed as a function of the estimated shower size.




(a) (b)

**Figure 9.** DELPHI a.) Distribution of the integral muon multiplicity, with absolute normalization, based on the measured highest intensity primary flux ((1) in Figure 10). b.) CORSIKA with QGSJET, or J.Hörandel's version [44] for modified p-nucleus cross-section. Again flux (1) is used.

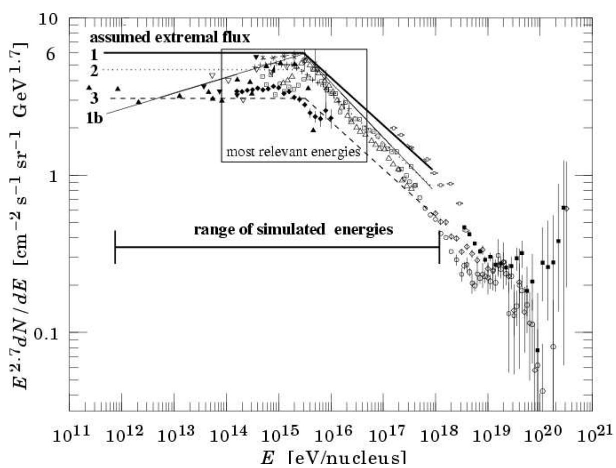
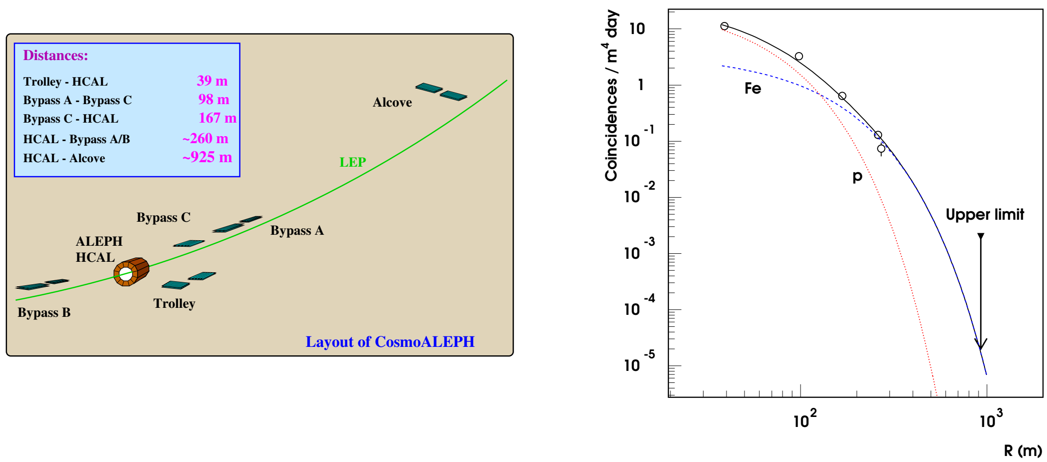



**Figure 10.** Specific primary fluxes used by ALEPH in their analysis. (1) is the highest intensity measured flux.

## 6. Lateral distribution of high energy muons; Cosmo-ALEPH

ALEPH had installed 5 sets of scintillator modules along the beam-line (Figure 11 a). Coincidences among them, as well as with the HCAL of the ALEPH-detector, were recorded. The number of coincidences per m$^4$

and day are shown in Figure 11 b), and compared to expectation. Also this type of analysis favours heavy primaries in the knee region [45].




(a) (b)

**Figure 11.** a.) Layout of the five scintillator stations of Cosmo-ALEPH. Each station consisted of several sets of coincident scintillator pairs. b.) Measured coincident rates between two unit detectors as a function of their distance.

## 7. Search for point sources

The search for point source signals through high energy muons faces experimental difficulties: $\gamma$ - induced showers produce less muons than proton induced ones, and according to existing measurements, LEP detectors have no chance to observe steady signals from known sources. But flare signals from blazars, AGN, or Gamma Ray Bursts (GRB) may be observed.

The experimental advantages are manyfold:

- A sky survey for Zenith angles between $0^o$ and $60^o$).
- Continuous acquisition.
- Low muon threshold ($E_\mu \geq$20 GeV, $E_\gamma >$ 200 GeV, for L3+C).
- Selection of the $E_\mu^{\mathrm{Thr.}}$ off-line (optimisation of the signal to background ratio).
- The background is continuously monitored.
- Sources are followed accross the sky.
- Good angular - 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 $\mathrm{m}^2\mathrm{sr}$.

Cosmo-ALEPH has tried to correlate the observed direction of five muon bundles with $n_\mu > 75$ to a point source of TeV $\gamma$ signals. No known TeV $\gamma$-source could be associated to the bundles ("0" marks in Figure 12) (DELPHI made a similar study).

L3+C may have observed a very strong flare signal in August 2000 ("O" mark in Figure 12) located in the galactic northern hemisphere. It has been presented in a parallel session [46].

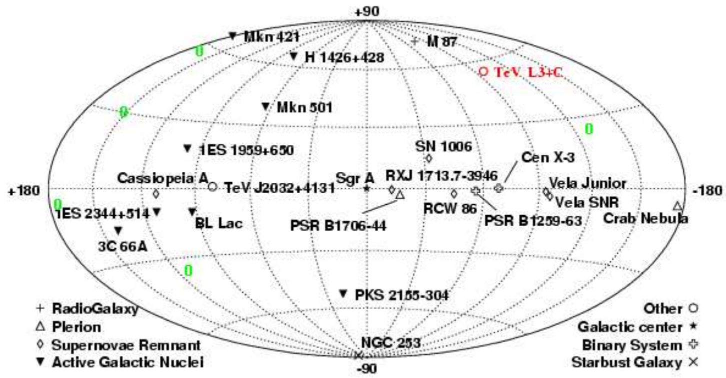



**Figure 12.** Compilation by T.C. Weekes (2003) [47] of TeV gamma sources with ALEPH's pointing directions of large multiplicity muon bundles (0) and L3+C's flare signal (o).

## 8. Anti-protons in space

The excellent angular resolution, the $0.1°$ pointing precision and the low momentum threshold allowed L3+C to observe the Moon shadow as a function of the Earth magnetic field. Due to the absence of a shadow on the East side of the Moon, a limit on the anti-matter to matter ratio could be obtained. In particular the limit on the antiproton to proton ratio around 1 TeV was set to 11 % with 90% confidence [48] (recently to 8% between 0.8 and 2.4 TeV, with a median energy of 1.2 TeV and for a muon energy threshold of 70 GeV [49]). The result is compared to direct measurements at energies below 50 GeV in Figure 13. These data agree with the secondary production model, but could be extrapolated to values up to several percents, near the L3+C limit at 1 TeV. MACRO observed the Sun shadow and got an upper limit on the antiproton to proton ratio of 52 % at a mean primary energy around 20 TeV [51]. Extrapolations from the measured muon charge ratio at ground level allow also to estimate upper limits on the antiproton content of the primary flux, but suffer from important systematic uncertainties [50]. Large anti-proton contributions can eventually be predicted in Dark matter models, like heavy Neutralino Anti-Neutralino annihilations.

## 9. Other topics studied by L3+C

- Eight GRBs were analyzed: GRB 990903, 990917, 991025, 991103, 991106, 000403, 000415, 000424. No signal for muons with energies above 30 GeV was found within 10 sec following the GRB time, in a 1 hour window around the GRB time, and within a 24 hour window.

- An interesting question is whether protons can be accelerated to more than 40 GeV in a particular solar flare. On the 14th of July 2000, around 10h30 UT, the sun was almost overhead Geneva, when a major flare ocurred. An upper flux limit of $\mathrm{I(E_p \geq 40GeV) \leq 2.8 \cdot 10^{-3}/(cm^2 s\, sr)}$ could be extracted from the data, assuming an $E_p^{-6}$ spectrum.

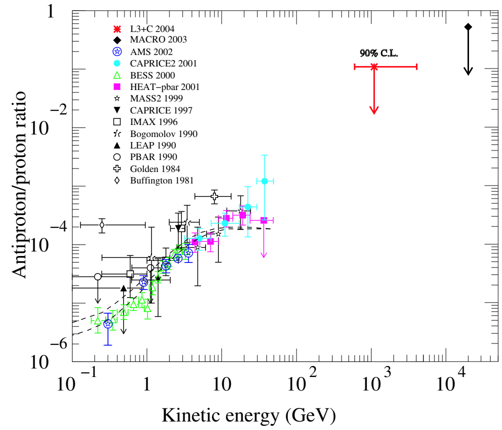



**Figure 13.** The Antiproton to proton ratio as a function of the kinetic energy of the nucleons.

- A search for Dark Matter (SUSY particles) has also been performed. We give here as an example the following preliminary result: An upper flux limit of $7.1 \cdot 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for a neutral, 200 GeV mass exotic particle with a momentum of 800 GeV, decaying into a neutral particle and two muons with opposite charge, was found. (LEP events $[WW \rightarrow \mu\,\mu\,\nu\,\nu]$ allow for checking the event filter and the scanning efficiency.)

- Directional anisotropies in the primary flux have been studied: L3+C's sensitivity to the anisotropy of the arrival direction of primaries is $10^{-4}$. No deviation from isotropy was observed at the sideral frequency for any of the first 3 harmonics. For muons above 20 or 30 GeV (corresponding to primary protons of $\sim$ 250 GeV) a significant departure from isotropy has been found for the 2nd harmonics at the Solar frequency.

- Environmental and meteorological effects are carefully analyzed in order to verify the sensitivity of the surface scintillator array to a possible solar flare signal.

## 10. Conclusions

LEP precision spectrometers have provided significant results in the field of cosmic ray physics. Four topics have to be mentioned: HE-interactions, composition, point sources and solar proton acceleration. Single and multi muons have been measured in the energy range between 20 and 3000 GeV.

- The atmospheric muon momentum spectrum, its angular dependence and the charge ratio have been measured with good precision between 20 and 3000 GeV. Good agreement is observed with recent low energy data (CAPRICE, BESS) ($50 < E_\mu < 300$ GeV) and, at large energy, with MACRO ($E_\mu > 1$ TeV). Presently existing hadronic interaction models used in transport calculations cannot correctly reproduce the observed high energy muon spectrum, for given primary flux. The atmospheric $\nu_\mu$- and $\overline{\nu_\mu}$- spectra can be better constrained (for $\nu$- oscillation studies), and the $\nu_\mu$-induced muon background for $\nu$-astronomy telescopes can be better defined.

- The study of muon bundles has demonstrated that low multiplicities favour protons as primaries, median multiplicities show a trend to heavier elements. High multiplicities cannot be explained even with iron nuclei, and high energy interaction models fail to explain the data in the energy region of the knee. In addition very high muon-multiplicity events have been observed, lacking an explanation (strangelets as primaries and other proposals have been discussed).

(More about the very forward physics at very high energies is expected from other future CERN based experiments: TOTEM, LHCf and ALICE.)

- No known point source emitting high energy gamma rays has been observed through muon bundles underground, but one flare signal may have been observed through single muons. Out of eight studied GRBs, none could be observed through secondary muons above 30 GeV, in 10 sec, 1h, or 1d time windows.

- Moon shadows could be observed for different muon momentum ranges, and an 11 % limit on the $\overline{p}/p$ ratio could be set around 1 TeV.

- An upper flux limit of protons with $E_p > 40$ GeV of the 14 July 2000 Solar flare could be given.

- An upper flux limit for a particular Dark Matter candidate could be determined.

- The Solar anisotropy of primary protons around 250 GeV has been observed.

## 11. Acknowledgements

The author would like to thank Petr Travnicek, Jan Ridky from DELPHI, Claus Grupen from Cosmo-ALEPH and Michael Unger from L3+C for the help to prepare this presentation and the critical reading of the manuscript.

## References

[1] D. Skobeltzyn, *Z.f.Phys.* **43** (1927) 354.
[2] C.D. Anderson, *Phys.Rev.***43** (1933) 491.
[3] S.H. Neddermeyer and C.D. Anderson, *Phys.Rev.* **51** (1937) 884;
S.H. Neddermeyer and C.D. Anderson, *Rev.Mod.Phys.* **11** (1939) 191.
[4] B. Rossi, *Rev.Mod.Phys.* **20** (1948) 537.
[5] D.E. Caro, J.K. Parry and H. Rathgeber, *Austral.J.Sci.Res.* **A 4** (1950) 16.
[6] B.D. Hayams, *et al. Proc.Phys.Soc.Lond.* **A 63** (1950) 1053.
[7] B.G. Owen and J.G. Wilson, *Proc.Phys.Soc.Lond.* **A 68** (1955) 409.
[8] A.L. Rodgers, P.D.thesis 1957, University of Manchester.
[9] J.L. Lloyd, E.Rössle and A.W.Wolfendale, *Proc.Phys.Soc.Lond.* **A 70** (1957) 421;
P.J.Hayman, N.S.Palmer and A.W.Wolfendale, *Proc.Phys.Soc.Lond.* **A 275** (1963) 391.
[10] B.C.Rastin, *J.Phys.G: Nucl.Phys.* **10** (1984) 1609.
[11] G.N. Fowler and A.W. Wolfendale, in Encyclopedia of Physics, Vol. XLVI/1, (1961), p. 272-281, ed. S. Flügge, Springer Verlag, Stuttgart.
[12] S.Higashi, T.Kitamura, M.Oda, Y.Tanaka and Y.Watase, *Nuovo Cim.* **32** (1964) 1.
[13] Y. Miyazaki, *Phys.Rev.* **76** (1949) 1733.
[14] P.H. Barrett, M.L. Bollinger, G.Cocconi, Y. Eisenberg and K.Greisen, *Rev.Mod.Phys.* **24** (1952) 133.
[15] E.V.Bugaev, *et al.*, *Phys.Rev.* **D 58** (1998) 054001.
[16] T. Hebbeker and Ch. Timmermans, *Astropart.Phys.* **18** (2002) 107.
[17] L3+C collab.: O. Adriani *et al.*, *Nucl. Inst. Meth.* **A 488** (2002) 209.
[18] The Cosmo-ALEPH collaboration: N.O. Hashim et al., these proceedings, HE 1.1.
[19] L3 collab.: P.Achard *et al.*, *Phys. Lett.* **B 598** (2004) 15.
[20] BESS Collaboration, T. Sanuki, *et al.*, *Phys.Lett.* **B 541** (2002) 234;
BESS Collaboration, T. Sanuki, *et al.*, *Phys.Lett.* **B 581** (2004) 272, Erratum;
BESS Collaboration, S. Haino, *et al.*, *Phys. Lett.* **B 594** (2004) 35.

[21] CAPRICE Collaboration, J. Kremer,*et al.*, *Phys.Rev.Lett.* **83** (1999) 4241;
CAPRICE Collaboration, M. Boezio,*et al.*, *Phys.Rev.* **D 67** (2003) 072003.
[22] O.C. Allkofer, K. Carstensen and D.W. Dau, *J.Phys.* **G 1** (1975) 584.
[23] C.A. Ayre, *et al.*, *J.Phys.* **G 1** (1975) 584.
[24] G. Giacomelli, private communication, NOW 2004.
[25] P. Pascale, *et al.*, *J.Geophys.Res.* **98** (1993) 3501.
[26] B.J. Bateman, *et al.*, *Phys.Lett.* **B 36** (1971) 144;
P.J. Green, *et al.*, *Phys. Rev.* **D 20** (1979) 1598.
[27] L3+C Collaboration, M. Unger, *et al.*, Proc. 19th ECRS 2004.
[28] AMS Collaboration, J. Alcaraz, *et al.*, *Phys.Lett.* **B 490** (2000) 27;
BESS Collaboration, T. Sanuki, *et al.*, *Astrophys.J.* **545** (2000) 1135;
[29] M. Honda, *et al.*, *Phys.Rev.* **D 52** (1995) 4985.
[30] V. Agrawal, *et al.*, *Phys.Rev.* **D 53** (1996) 1314.
[31] R. Engel,T.K. Gaisser, T. Stanev; Proc. 27th ICRC (2001) 1029.
[32] D. Heck, *et al.*, Technical report, FZKA 6019, Forschungszentrum Karlsruhe (1998).
[33] R. Engel, T.K. Gaisser, P. Lipari, T. Stanev, Proc. 27th ICRC (2001) 1381.
[34] N.N. Kalmykov, *et al.*, *Yad. Fiz.* **56** (1993) 105;
N.N. Kalmykov, *et al.*, *Nucl.Phys.Proc.Suppl.* **B 52** (1997) 17
[35] R.S. Fletcher, *et al.*, *Phys.Rev.* **D 50** (1994) 5710; R. Engel, *et al.*, Proc. 26th ICRC (1999) 415.
[36] M. Honda, *et al.*, *Phys.Rev.* **D 70** (2004) 043008.
[37] J. Ranft, *Phys.Rev.* **D 51** (1995) 64;
R. Engel and J. Ranft, *Phys.Rev.* **D 54** (1996) 4244;
S. Roesler, R. Engel and J. Ranft, Proc. ICRC 2001, Hamburg.
[38] T. Sanuki et al., Proc. 29th ICRC, Pune, 9, 139 (2005).
[39] V. Andersen, *et al. Adv.Space Res.* **34** (2004) 1338.
[40] G. Fiorentini, V.A. Naumov and F.L. Villante, *Phys.Lett.* **B 510** (2001) 173.
[41] D. Heck, *et al.*, Technical report, FZKA 6019, Forschungszentrum Karlsruhe (1998).
[42] V. Avati, *et al.*,*Astropart.Phys.* **19** (2003) 513.
[43] DELPHI Collaboration, J. Ridky and P. Travnicek, *Acta Phys.Polon.* **B 35** (2004) 1813.
[44] J. Hörandel, *J.Phys.* **G 29** (2003) 2439.
[45] Cosmo-ALEPH collaboration, C. Grupen, H. Wachsmuth and A.A. Mailov, private communication.
[46] P. Le Coultre, Proc. 29th ICRC, Pune, 4, 399 (2005).
[47] C.T. Weeks, *New Astron. Rev.* **48** (2004) 527.
[48] L3 collab.: P. Achard, *et al. et al.*, *Astropart.Phys.* **23** (2005) 411.
[49] YuPeng Xu, phD thesis, ETH Zürich, 2005.
[50] S.A. Stephens, *Astron. Astrophysics* **149** (1985) 1.
[51] MACRO collab., M. Ambrosio, *et al.*, *Astropart.Phys.* **20** (2003) 145.
[52] MACRO collab.: M. Ambrosio, *et al.*, *Astropart.Phys.* **18** (2002) 615;
NUSEX collab.: G. Battistoni, *et al.*, *Phys.Lett.* **B 115** (1985) 465. .
[53] SOUDAN collab.: M.L. Marshak *et al.*, Phys.Rev.Lett. **54** (1985) 2079, and **55** (1985) 1965, and M.A. Thomson *et al.*, Phys.Lett. **B 269** (1991) 220.
[54] MILAGRO collab.: R. Atkins *et al.*, *Astrophys. J.Lett.* **533** (2000) L119, and **525** (1999) L25.