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CONCLUSIONS OF UPPSALA CONFERENCE
ON EXPERIMENTATION AT LEP

Erwin Gabathuler
CERN, Geneva, Switzerland

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1. INTRODUCTION

The main theme of this conference has been to review the experimental techniques associated with detectors operating at storage rings. The detailed results of what has been and will be achieved at PETRA, PEP and $p\bar{p}$ collider programmes will be used to design the next stage of detectors for LEP. However, before proceeding to highlight the various experimental techniques which will require further development, we should remind ourselves briefly of some of the physics goals which will have to be achieved in the early days of LEP running. Clearly the physics will be concentrated in the region around the Z^0 pole, and will be based on one photon exchange processes with an initial luminosity of perhaps a few $\times 10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$.

An experiment can be carried out using the process $(e^+e^- \rightarrow Z^0 \rightarrow Q\bar{Q})$ to scan the Z^0 peak and measure the mass and width precisely, using the energy steps given by the machine. The detector requirements can be modest, since the event rate is several hundred events/day. The next stage would be a determination of the various quark flavours and their cascade decays in order to measure the mixing angles. Immediately the problems of small branching ratios into fully reconstructed final states which have bedevilled charm and beauty searches in both fixed-target and storage ring physics when more than one flavour is involved become apparent. The only way out at present appears to be good measurement of the momenta of charged tracks and good electromagnetic and hadronic energy measurement together with some particle identification for large $p_{\perp}$ leptons relative to the jet axis.

A study of the reaction $e^+e^- \rightarrow L^+L^-$ when L is any lepton e, μ, τ to study asymmetries induced by the weak interaction requires knowledge of the sign of the charge, good measurement of the angular distribution as well as lepton identification. This again imposes detector requirements very similar to those required for a study of quark cascades.

The most difficult part is to decide what are the necessary criteria required to design a detector to do a specific physics programme as well as possible, and then to achieve that goal in practice. However, it is worth pointing out here

that at PETRA it was possible for all groups to reach the most interesting physics with detectors of widely different detection properties. This highlights the simplicity of the physics at an electron-positron machine.

Before proceeding on a tour of general properties of LEP-type detectors, it is useful to remember the following points:-

- a) The most probable charged particle momentum is ~ 6 GeV/c and single photon (π^0) energy ~ 2 GeV. Essentially half of all the particles in an event have a momentum less than 2 GeV/c.
- b) Two-photon interactions are still a large source of background in comparison with one-photon events. At an energy of 50 GeV/beam the 2γ cross-section is $\sim 10^4$ larger than the 1γ cross-section. These events are produced mainly along the direction of the beams and can be separated using total energy and $p_{\perp}$ constraints. They are of course interesting to study in their own right, and will provide important information on the structure function of the photon analogous to that from deep inelastic scattering off nucleons.
- c) We have heard in a previous talk on physics at PETRA⁽¹⁾ that there are a large number of final state $N\bar{N}$ baryons ($\sim 40\%$ of all events at a $\sqrt{s}$ of 30 GeV). This is somewhat surprising, and could just depend on the total energy available for the leading quark as predicted by the quark-parton model in deep inelastic scattering at high energies⁽²⁾.
- d) Pattern recognition problems will be severe due to the large number of charged particles ($\langle N_{ch} \rangle \approx 25$) predicted at these energies. A large fraction of K_S^0 and possibly Λ^0 decays coming from sequential cascades of heavy quarks will add to the difficulty.
- e) With the present design, the closest distance between the interaction point and the surface is ~ 45 m. This will require new ideas on installation and operation of experiments. However, the new SPS collider experiments will provide relevant experience in that direction.

2. MAGNETIC FIELD AT VERTEX

The first question to ask in the design of any detector is do we require a magnetic field at the vertex. If there is no field, then the straight tracks give good angular precision and we have to rely on the detector for a precise measurement of the energies of the particles. So far, the Crystal Ball detector⁽³⁾ and the CUSB detector⁽⁴⁾ have shown that good physics can be achieved using detectors which measure electromagnetic energy with excellent resolution using NaI. The energy resolution of NaI has a $E^{-0.25}$ dependence which would suggest that a detector of this type could be used at LEP to measure total electromagnetic energy or transitions involving single gamma rays, e.g. $Z^0 + \gamma$. The increase in charged multiplicity and jet-nature of charged and neutral particles with energy will introduce confusion in separating charged and neutral energy unless the inner diameter of the detector is increased. The cost of these detectors however scales as the cube of the diameter. The CUSB detector is illustrated in Fig. 1(a) and the power of the detector to produce quick results is shown in Fig. 1(b).

In general most experimental detectors use magnetic fields, as can be seen in Table I, where the field strengths for the different detectors at existing storage rings are presented, together with their ability to detect different particles. The majority of these devices use magnetic solenoids, since the shielding of electron beams from transverse magnetic fields introduces many problems associated with material near the beam region. The charged particle momentum resolution scales like BL^2 where B is the field strength and L is the radial distance. Essentially we have then a choice between a solenoid of large radius and low field strength or small radius and high field strength. The former has advantages of low cost, large volume, large track length for multiple sampling (dE/dx), useful time-of-flight and the possibility of putting electron/photon calorimetry inside the coil. In the high field solution, the volume is limited by cost, but because of small coil thickness (for superconducting coils ~ 0.5 r.l.), the dimensions required for electromagnetic and hadronic calorimetry outside the coil

can be kept small. With the higher field, the charged particles of opposite sign are well fanned out, since for fixed Bl^2 the bending angle $\phi \propto Bl$. However, if ϕ is large, tracks can cross in projection along the magnetic field lines which introduces pattern recognition problems. The momentum resolution which can be achieved for various field strengths and size of solenoid has been discussed at this conference⁽⁵⁾ and is presented in Fig. 2. In addition, the onset of spiralling of 300 MeV/c particles is shown. A typical event for the TASSO⁽⁶⁾ and CELLO⁽⁷⁾ detectors is illustrated in Fig. 3(a) & (b), and indicates the importance of having many track samplings in order to resolve all the tracks. Careful studies should be made in order to minimise the power requirements of large volume solenoids using conventional coils, in particular the criterion which determines the length of the solenoid and possible use of end-shaping.

3. POSITION MEASUREMENT

The precision which can be achieved in the determination of the momentum is a product of the number of co-ordinates and the resolution in $R\Delta\phi$, the plane of magnetic deflection. At present the limitation in the spatial resolution of large area drift chambers is $\sim 200\mu$ (r.m.s.) and it is evident from this conference⁽⁸⁾ that it should be possible to achieve a figure of 100μ by a careful study of the systematic uncertainties introduced by mechanical tolerances, time/space correlation and improved electronics. The limitation in the determination of the R_z co-ordinate is given by the following methods:-

1. Small angle stereo 3-5 mm
2. Delay line 5 mm
3. Cathode strips 0.4 mm
4. Charge div. 1% per metre
5. Drift time measurement 0.2 mm (TPC)

At LEP, the charged multiplicity is much higher and therefore the two-track ambiguity increases. The reconstruction of final-state particles to determine flavours will require good R_z spatial resolution, and therefore more development work

is required in this area. In fact for large-scale drift systems, much more care should be given in the initial design to the on-line control of alignment and space/time calibration. Here the use of lasers is showing promising results and should be further developed. The existing state of the art for magnetic tracking in the existing detectors is given in Table II.

For small spatial detectors, it would seem desirable to build a miniature high-precision spatial detector for detecting short-lived particles, which could be used in conjunction with a large magnetic detector analogous to the LEBC⁽⁹⁾ and BIBC⁽¹⁰⁾ chambers at the SPS. Such a futuristic device is illustrated in Fig. 4, where solid-state detectors are placed right inside the vacuum chamber in which the pre-amplifiers are embedded. The vacuum chamber is then surrounded by a short cylindrical high-precision single cell drift chamber containing many wires, which would provide a spatial resolution in the region of 40μ . Such a device could also be envisaged for triggering on high-mass flavours. This is a very challenging problem, which if solved successfully could revolutionise our ideas on detector size.

4. PARTICLE IDENTIFICATION

The identification of charged particles is the area in which there have been the most spectacular advances in recent years. In particular, as can be seen in Table III, the development of aerogel, Čerenkov ring imaging and especially dE/dx measurements has extended the range of particle identification up towards 50 GeV/c for storage ring detectors.

In the low-momentum range where most of the particles exist, time-of-flight is an excellent technique, since it is simple to construct and uses little space. It has been shown at this conference⁽¹¹⁾ that it is possible to achieve a resolution of the order of 200 picosecond using thick plastic counters, and here is an area where every effort should be made to push the limits down towards 50 picosecond, thus extending K-P separation into the 4 GeV/c region for a flight path of 1.50m. Some developments in this direction have been reported using planar spark

counters developed by Pestov⁽¹²⁾ and in secondary emission techniques⁽¹³⁾, but there are still improvements which can be made using standard techniques in conjunction with the manufacturers of scintillators and phototubes. A planar spark counter using semi-conducting glass with a resistivity of $\sim 10^{10}$ ohm/cm is illustrated in Fig. 5, in which a time resolution of 50 picosec. has been achieved.

One of the most difficult areas in particle detection has been in the momentum region between time-of-flight operation and gas Čerenkov operation, corresponding to particle identification in the 1 - 5 GeV/c region ($\gamma = 5 - 10$). Recently, the development of silica aerogel material at DESY, Lund and Saclay has resulted in the production of counters with refractive indexes in the region of 1.02 to 1.03 for the AFS⁽¹⁴⁾, EHS⁽¹⁵⁾, EMC⁽¹⁶⁾ at CERN and for TASSO⁽¹⁷⁾ at DESY. Further development of this technology to achieve a refractive index of 1.006 is under study, and would have many applications where high-pressure Čerenkov counters are required.

The development of ring-imaging Čerenkov detectors is a difficult area, due to the mismatch between the Čerenkov light produced in the gas medium and its conversion into ionisation in a spatial detector. However, as we have heard at this conference⁽¹⁸⁾, the problems are being solved, and the very nice ring images produced by 10 GeV/c pions in Argon using a photoionising gas (TEA) show that there is progress in this field. However the techniques required in going from a small development to a modest size detector are very challenging, and a successful outcome will have a tremendous impact in all areas of physics.

The measurement of energy loss (dE/dX) has shown great progress following the pioneering by the ISIS⁽¹⁹⁾ and JADE⁽²⁰⁾ groups with important contributions from the EPI at CERN⁽²¹⁾ and the TPC at PEP⁽²²⁾. The technique is to measure the relativistic rise as illustrated in Fig.6(a) by frequent samples in a gas, and determine a truncated mean. The most probable energy loss in one cm Argon at 10 atm is illustrated in Fig.6(b), and shows that K - P separation requires a resolution of the order of a few %.

The results which have been achieved so far are plotted in Table IV for the various detectors and show that with the exception of ISIS there is a discrepancy between the experimental and theoretical resolutions. However it is worth noting that in the ISIS detector only one array of wires and electronics is used for all the measurements, and very detailed investigations were made into the choice and purity of gas, base-line restoration and pulse integration. In spite of much talk of $\sqrt{2}$ factors at this conference⁽²³⁾, we shall surely find agreement between theory and experiment after the experimentalists have carefully analysed their data. Essentially we should believe in QED. The rapid advance in the field of flash ADC's⁽²⁴⁾ and CCD's⁽²⁵⁾ will provide a new dimension to this technique and detailed studies should be carried out in the use of a very large diameter Argon detector. It should be possible to achieve π - K separation between 2 - 20 GeV/c using a 2.5 metre track length and 170 samplings in Argon gas at one atmosphere⁽²⁶⁾.

The next stage in this field could be that of counting individual clusters, i.e. the primary ionisation, and thus avoiding the Landau fluctuations. A start has been made in this direction, and preliminary results have been presented at this conference⁽²⁷⁾. The concept of simple counting techniques appears to be the right direction in which to proceed, but it is evident that a lot more development will be needed if the simplicity of the method is to be maintained.

5. CALORIMETRY

The use of calorimetry in storage-ring detectors has become more important as the energies have increased. For charged particles, the momentum resolution scales with p for a magnetic detector and with $p^{-0.5}$ for calorimetry. Therefore the combined use of magnetic tracking and calorimetry allows good momentum and energy measurements as well as providing particle identification. In particular, if we are trying to measure total energy, then the calorimetry is essential for measuring the neutral hadrons and photons. The recent developments of low-cost scintillator and wavelength shifter for integration of the light onto a single photomultiplier have simplified the design of these detectors.

A detailed presentation on the limiting factors which contribute to the energy resolution of calorimeters has been given at this conference⁽²⁸⁾. For any sampling calorimeter of infinite length, the intrinsic energy resolution is given by

$$\frac{\Delta E}{E} = (A^2 + R^2)^{\frac{1}{2}}$$

where A is given by the photon statistics and R is due to sampling fluctuations. For electromagnetic detectors, the first term can be neglected and we can write

$$R = 3.2\% \left[\frac{(\text{MeV}) t (\text{r.l.})}{P \cdot E (\text{GeV})} \right]^2$$

where ξ is the critical energy and P is a complex factor which not only takes into account the shortening of the track length due to the cut-off energy E_c , but also includes the effect that low-energy electrons are produced at larger angles in high Z materials. This formula gives good agreement with results obtained from Monte-Carlo techniques, and shows clearly why the best resolution is obtained for high Z materials. Since the lateral development of the shower is given by Molière scattering to be $\propto 7A/Z$ gcm^2 , then the use of high Z material is necessary to avoid jet overlap problems in pattern recognition for electromagnetic calorimeters. At present the best detector for large area application is the liquid Argon calorimeter, which combines good spatial and energy resolution with simple energy calibration. However the cost and operation of such a detector below ground level will certainly introduce limitations in its application. Sandwich detectors of lead/scintillator suffer from poor positional accuracy, while lead/proportional chambers have a factor of 2 worse energy resolution due to Landau fluctuations and fluctuations in large-angle electron tracks in gas. The latter are the dominant cause of the poorer resolution. More development is required in this area, but we have to guard against detectors which contain so much information that the read-out and analysis becomes prohibitive. The properties of the present electromagnetic calorimeters available in storage rings are presented in Table V. At LEP energies, 50% of the photons will still have energies less than 2 GeV, and the properties and location of the detector will depend on the flavour of the physics to be done.

For hadronic calorimeters, the limit in energy resolution is in the region of $50\% E^{-\frac{1}{2}}$ due to the fluctuations arising from the electromagnetic component and the nuclear component of the hadronic shower. The difference in response is related to the fact that part of the energy in the nuclear component remains immeasurable due to the nuclear binding energy. The effect of varying the thickness of the sampling medium is clearly shown in Fig. 7. It shows that below 3cm iron there is essentially no gain in resolution, while the effect of increasing the thickness causes us to lose the response of fast protons produced in the iron and eventually the electromagnetic energy in the hadronic shower. High multiplicity at LEP energies requires further development of the concept of granularity, where each calorimeter section behaves like a crystal ball section. However the problems of extracting the scintillation light, and minimising that produced in the wavelength shifter due to showers, still leaves room for new ideas and techniques to be developed. For small detectors, the use of optical fibres offers possibilities of flexibility. The resolution which has been achieved in hadron calorimeters for storage ring experiments is presented in Table VI.

6. TRIGGERING, MONITORING AND CALIBRATING

The indications are that the present techniques of using coarse granularity, i.e. groups of wires etc, to provide kinematic reconstruction of tracks are sufficient to reduce the trigger rate from a few kiloHertz to a few Hertz and should also be satisfactory at LEP energies. The main difficulty arises if we demand only one track in the trigger due to low energy spirals. However with a combination of particle momenta and calorimetry it should be fairly straightforward to devise low-rate triggers. For those detectors which have a magnetic field over the vertex, it is important to have simple algorithms for magnetic tracking, and therefore the field should be uniform in the vertex region. The development of Fastbus, as mentioned earlier at the conference⁽²⁹⁾ should be explored with respect to triggering etc for LEP detectors.

As the demands on precision and more information per event increases, then the necessity of having a detector which contains many thousands of channels operating in a well-defined efficient manner becomes even more crucial. At this conference⁽³⁰⁾ we have heard about new developments in the use of lasers to provide ionisation in gaseous detectors for calibration. Lasers have already been used with optical fibres to provide timing and analog signals for relative calibration of shower detectors, but this should be extended to provide absolute energy calibrations. Clearly more work is required here, in particular the development of a simple system which gives a fast response to a change in efficiency of any part of the detector. Essentially if we have to spend a lot of effort and time in providing a monitoring system for a large detector, then it should be a single system which works more reliably than the detector itself.

7. CONCLUSIONS

In conclusion, we have a lot of work to do in extending present ideas and building on the experience gained at PETRA, PEP and the SPS collider programme, since there does not appear to be any revolutionary new detector in sight. There are many areas of detector development involving not only the detector but also read-out, monitoring and calibration where, with a modest investment of time and effort, improvements and simplifications can be made. However, the important thing is to start now. To this end, CERN is willing to provide some financial support to universities and small institutes using CERN who may wish to carry out technical development on detectors with LEP connections. Finally we should always be ready for surprises, and perhaps we have already been given a warning of what to expect from the Burial Grounds of the former Kings of Uppsala as illustrated in Fig. 7.

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DETECTOR	MAGNET (T)	VERTEX	PARTICLE IDENTIFICATION			
			μ	e	γ	h
JADE	0.45	Imag. DC	•	•	•	•
TASSO	0.5	DC	•	•	•	•
CELLO	1.3SC	PWC+DC	•	•	•	
MARK J	Iron toroid	DC/PC	•	•	•	
CLEO	0.5	DC	•	•	•	•
MARK II	0.4	DC	•	•	•	
AFS	0.5	Imag. DC		•	•	•
TPC	1.5SC	Imag. DC	•	•	•	•
MARK III	0.4	DC	•	•	•	
Crystal Ball	NO	NO		•	•	
CUSB	NO	DC		•	•	

Table I. General properties of detectors at storage rings.

Type		Track		Spatial Resoln		σ_p/p^2 % GeV^{-1}
		radial length (mm)	samplings	$r_\phi(\sigma)$	$z(\sigma)$	
imaging DC 4 atm	JADE	600	48	180 μ	16mm	3.3
minimal DC small $\times$ stereo	TASSO	855	15	$\geq 220 \mu$	3-4mm	2.2
PWC cath.r.o. + min. DC	CELLO	530	12 r_ϕ 5 z 5 30°	180 μ	0.4mm	1.5*
min. DC small $\times$ stereo	CLEO	800	17	250 μ	5mm (0.3mm)	5.0
min. DC small stereo	MARK II	1034	16	200 μ	4mm	1.9
imag. DC 1 atm	AFS	600	42	250 μ	17mm	2.5
imag. DC 10 atm	TPC	800	185 dE/dx 15 r_ϕ	100 $\mu^{**} \leq 0.2\text{mm}^{**}$		$\sim 1.0^*$
imag.	UA1	1120	$\times$ depend.	drift: 250 μ ch.div.: 8-25mm		

* Inferred from space resoln

** Small test chamber

Table II. Momentum resolution obtained for different detectors.

Table III. The techniques available for π , K, p separation in the energy range 1 - 50 GeV.

DEVICE	PA/MOM(GeV)	EXP($\frac{\Delta E}{\sigma}$)	TH($\frac{\Delta E}{\sigma}$)	RATIO
ISIS	π/e 0.5	8.0	8.1	1.01
CRISIS	p/π 40	2.16	3.2	1.48
EPI	p/π 50	5.1	6.1	1.2
TPC	π/e 0.8	11.8	18.0	1.36
JADE	π/e 0.45	4.2(JET)	7.8	1.86
"	" "	5.0	7.8	1.56
HRS	π/e 4	3.2	4.1	1.32
CLEO	π/e 0.45	8.25	11.1	1.36

Table IV. A comparison of experimental and theoretical results achieved with different detectors.

	Type	$\frac{\Delta R}{4\pi}$	Thickn. X_0	Energy Res. $\sigma_E/E(\%GeV)^{-2}$	Angular Res. r.m.s.	Comments
JADE	Pb glass	.90	12.5	$\sqrt{(6/\sqrt{E})^2 + 3.5^2}$	7mrad	
TASSO	Pb/LAr	.90	14	$10/\sqrt{E}$	2.5mrad	prototype test
CELLO	Pb/LAr	.96	21	$8.5/\sqrt{E}$	4mrad	" "
MARK J	Pb/Sc	$6X_0: .96$ $18X_0: .85$	18	$12/\sqrt{E}$	$\theta: 3^0 - 5^0$ $\psi: 7^0$	
CLEO	Pb/PropT	.68	10-12	-	-	
MARK II	Pb/LAr	.69	14	$11.5/\sqrt{E}$	high $E_e: 3.6$ low $E_\gamma: 8$)mrad	
TPC	Pb/MWPC	.98	14	$12/\sqrt{E}$	< 10mrad*	granularity*
AFS	U/Sc	.71	6	$14/\sqrt{E}$	-	
UA1	Pb/Sc	1.0	23	$9/\sqrt{E}$	-	
MARK III	Pb/MWPC	.97	12	$16/\sqrt{E}$	-	
Xstal Ball	NaI	.94	16	$2.3/4\sqrt{E}$ $(1.2/4\sqrt{E})^{**}$	1^0	test**

Table V. The energy and angular resolution achieved for storage ring electromagnetic detectors.

DETECTOR	RESOLN	ENERGY RANGE (GeV)
AFS (R806)	$30\%/\sqrt{E}$	$1 < E < 10$ 1.7mm U/LAr
MARK J	20%	$\sqrt{s} = 30$ Fe/Sc
MAC	$75\%/\sqrt{E}$	2.7cm Fe + prop.
UA1	$80\%/\sqrt{E}$	$1 < E < 80$ 5cm Fe BBQ
UA2	$60\%/\sqrt{E}$	1.5cm Fe BBQ

Table VI. The energy resolution of various hadron calorimeters in storage rings.

FIGURE CAPTIONS

Fig. 1 a) The CUSB detector at CLEO.

b) The on-line R-meter results using simple energy and logic discrimination

Fig. 2 The momentum resolution available in a solenoid as a function of radices and field strength. The curves apply to a 10 GeV/c particle, whose sagitta is measured with a precision of 100 μ m.

Fig. 3 a) An event in the TASSO detector.

b) An event in the CELLO detector.

Fig. 4 A small high-precision detector to measure short-lived particle decays.

Fig. 5 A planar spark chamber as developed by Y N Pestov.

Fig. 6 a) The relativistic rise of the energy loss for charged particles.

b) The most probable energy loss for different particles in 1 cm of Argon at 10 atm.

Fig. 7 The resolution as a function of absorber thickness in a hadronic calorimeter. The black points correspond to predictions for 23 GeV hadrons.

Fig. 8 Surprises at LEP from the former kings of Uppsala.

Fig. 1

Fig. 2

	51	LAR	TRIGGER	621	
109		65	75		82
62	35 +Z	35	69	83 63 -Z	32 96
71		433	67		52
	185			82	

	92	LAR	TRIGGER	467	
109		79	76		75
111	20 +Z	19	87	80 66 -Z	30 109
231		108	84		64
	558			65	

CELLO

a

TASSO

b

Fig. 3

Fig. 4

PLANAR SPARK COUNTER (SCHEMATIC)

S.C. GLASS-RESISTIVITY : $10^9 / 10^{10} \Omega \cdot \text{cm}$
 GAP WIDTH : $0.1 \text{ mm} \pm 0.2 \text{ mm}$
 PLANARITY : $\lesssim \pm 2 \mu\text{m}$
 GAS PRESSURE : $\sim 10 \text{ BAR}$
 GAS FLOW : $\sim 1 \text{ ms}^{-1}$

Fig. 5

Fig. 6

Fig. 7

"REMINDER" FROM THE FORMER KINGS
IN UPPSALA

Fig. 8

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