Department of Experimental Particle Physics *(F-9)*

Departmental research is devoted to measurements in the world of elementary particles, disclosing the ultimate building blocks of matter and the nature of interactions between them. Experiments are carried out within large collaborative programmes at international centres for particle physics at CERN near Geneva and at DESY in Hamburg. Such measurements demand technologically advanced particle detectors, and the Department is also engaged in their development and application.

Head
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In 1998 the CPLEAR collaboration with the participation of Slovenian experimental particle physicists published the first direct experimental evidence for the existence of a microscopic arrow of time.

In order to reveal the ultimate secrets of nature in the world of elementary particles, accelerators with higher and higher energies are needed. Their cost, both in terms of money and human resources, has grown to the level that they became affordable only as a joint enterprise of all mankind. Thus, future accelerators will be unique facilities of their kind, the first being the Large Hadron Collider (LHC) constructed in the European laboratory for particle physics (CERN) near Geneva. All the researchers in the field will exploit this facility jointly to perform experiments in the energy regions as yet inaccessible to humans, but still far from the vast blast of the Big Bang which led to the creation of the Universe.

Together with colleagues from the Physics Department of the Faculty of Mathematics and Physics and the Faculty of Electrical Engineering of the University of Ljubljana, and from the Faculty of Chemistry and Chemical Technology of the University of Maribor, we are making measurements at the European Laboratory for Particle Physics (CERN), Geneva, and the German centre DESY in Hamburg. We are taking part in four experiments, each of which is conducted as an international collaboration:

- ATLAS at the Large Hadron Collider (LHC) at CERN (1600 researchers, 148 institutions),
- CPLEAR at the Low Energy Antiproton Ring (LEAR) at CERN (120 researchers, 16 institutions),
- DELPHI at theLarge Electron Positron collider (LEP) at CERN (550 researchers, 52 institutions) and
- HERA-B at the HERA electron-proton collider at DESY (310 researchers, 32 institutions).

The lifetime of an experiment is unique to the field of high energy physics, its duration ranging from five to more than twenty years. It has to go through the phases of planning, R & D, construction of the apparatus, several years of acquiring data, its analysis in terms of physics, followed by publication of the results. Except for the later phases of construction and data-acquisition which necessarily take place at the research centres, the other activities are distributed to home laboratories of the collaborating institutions. The necessary coordination is achieved through electronic media (World Wide Web, e-mail, video conferencing), although frequent meetings of groups and subgroups still prove to be essential. In larger experiments these meetings almost resemble workshops or even conferences, both in the number of participants and in the level of presentations.

Although the field is devoted to basic research into the nature of the Universe, the very existence of a joint endeavour of this magnitude constitutes an ideal breeding ground for new products and technologies. Developed primarily to make the experiments feasible, many of them find widespread application in other areas. The obvious showcase is undoubtedly the World Wide Web. Conceived at CERN as a communication exchange facility for the big collaborations at the LHC, it has in the past years developed into a indispensable tool in almost every field of human endeavour.

ATLAS Collaboration

In June 1996 the Slovenian group became the 148th institution to join the ATLAS project. They will build jointly a general-purpose detector to observe 14 TeV proton-proton collisions at the LHC. The detector is expected to be operational by mid 2005.

Our researchers are collaborating on the Semiconductor Tracker (SCT) which is part of the ATLAS Inner Detector. They have developed the production technology for large scale flexible printed circuits on aluminium-Kapton laminates, for use as power and DC-level signal supply cables to the tracker modules. In collaboration with the BALDER company from the Technological Park an exposure table for substrates with dimensions up to 8 x 0.5 m^2 was constructed. In the ELGO-LINE foundry near Cerknica, prototype cables were produced and subsequently tested successfully at a detector module test set-up at CERN.

The programme devoted to radiation hardness of silicon detectors has been continued. Its goals are to understand the basic mechanisms of defect generation and annealing, and to test the radiation resistance of detectors. To study the mechanisms, simple *p - i - n* structures on high-resistivity silicon were irradiated with fast neutrons from the Institute's TRIGA reactor. A strong influence of the electric field on radiation damage was discovered (Fig. 1). Within the ROSE R&D programme (CERN RD-48) the influence of impurities, especially oxygen, on radiation hardness has also been studied. Research on the radiation hardness of silicon operating at liquid nitrogen temperature has been started within the CERN RD-39 collaboration.

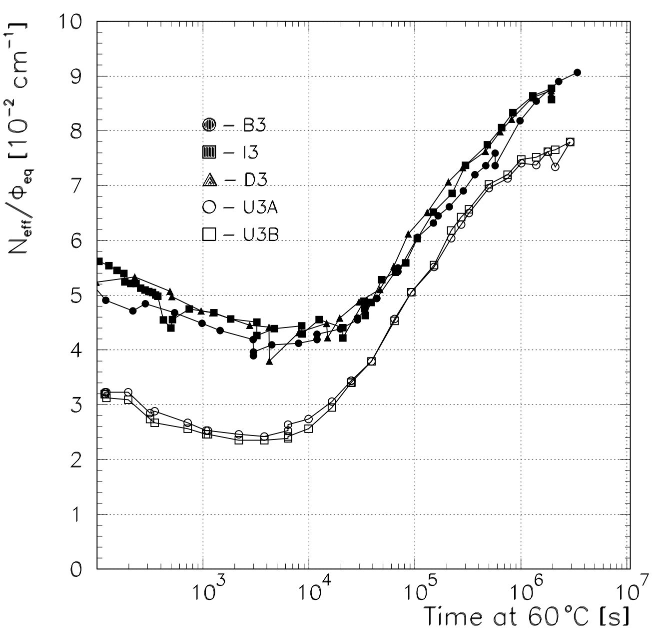

Figure 1: Development of radiation-induced defect concentration in silicon for neutron irradiated p - i - n structures with (filled marks) and without (open marks) applied bias. At the minimum, the defect concentration is about a factor of two worse in the case of biased structures

To test the radiation hardness of full-size detectors an additional irradiation site at the reactor was constructed. A tube leading to the centre of the reactor core, replacing three fuel rods, can house samples up to 78 mm in width. This should be sufficient to accept ATLAS SCT detector modules. Full-size detectors according to ATLAS specifications were irradiated at this site and subsequently tested with 40 MHz ATLAS prototype readout electronics.

CPLEAR Collaboration

The CPLEAR collaboration is completing the evaluation of parameters describing the violation of three fundamental discrete symmetries, CP, T and CPT in the neutral kaon system. In 1998 the emphasis was on the publication of results concerning semileptonic decays. In addition, results on CP-violation in decays to two or three neutral pions were published. The former measurement represents a novel approach to the determination of the parameter η_{00}, nearly independent of regeneration corrections. With the latter measurement, the accuracy of the CP-violation parameter η_{000} was improved by a factor of two.

A test of quantum mechanics in the context of the Einstein-Rosen-Podolsky paradox was published. The result confirms the non-separability of the two-kaon wave function, as postulated in quantum mechanics.

Four semileptonic decay rates can be measured by CPLEAR, characterized by the initial kaon strangeness and the decay lepton charge. Asymmetries between the rates reveal parameters of the neutral kaon system with high accuracy. From the asymmetry between decays in which the initial strangeness of the kaon had been reversed to that in which it had been kept, the mass difference between the longlived and shortlived component of the neutral kaon was measured with a relative accuracy of 3 x 10^{-17} of the kaon mass. An ingenious combination of asymmetries with data from decays into two charged pions enabled isolation of the CPT violation parameter in kaon mixing δ, independent of the eventual violation of CPT in decay. The result is consistent with CPT invariance, with the accuracy on the parameter improved by two orders of magnitude.

The most publicized achievement of CPLEAR, both within the scientific community and among the general public, was the first direct observation of time reversal violation (Fig. 2). Although expected as a consequence of CPT conservation since the discovery of CP failure 35 years ago, this discovery represents one of the most important results in particle physics in recent years. Time reversal violation manifests itself through a seven permille relative difference between rates for transformations of neutral antikaons into kaons and the time-reversed process of turning kaons into antikaons. The difference measured by CPLEAR exceeds its error by a factor of four, so that the possibility of the result being due to a random fluctuation is thus smaller than 3 x 10^{-5}.

DELPHI Collaboration

In 1998, LEP 2 collider operated at a centre-of-mass energy of 189 GeV, and delivered to each of its four detectors approximately 3000 W-pairs. This allowed for extensive tests of the present theory of fundamental particles and forces, known as the Standard Model, especially in the sector describing self couplings of the carriers of the weak and the electromagnetic interactions. Searches for the Higgs boson, a side product of the spontaneous symmetry breaking mechanism, have also profited from the gradually increasing energy of LEP 2.

We participated in data acquisition during a run lasting for six months. Apart from on-line quality checking of measured data, we also shared responsibilities for smooth operation and calibration of two sub-detectors of the DELPHI spectrometer, the ring imaging Cherenkov counter and the silicon tracker.

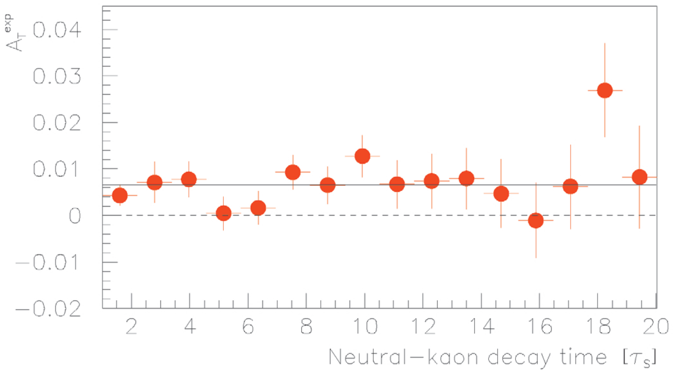

Figure 2: Time reversal asymmetry as measured with the CPLEAR experiment. The rate of transformation of $\bar{K}^0 \rightarrow K^0$ *is observed to exceed the time-reversed rate* $K^0 \rightarrow \bar{K}^0$ *by about seven permille. This measurement represents the first direct experimental observation of the arrow of time in the world of elementary particles*

Self couplings of carriers of the electroweak interactions differing from the Standard Model predictions would affect the total cross section for W^+W^- production as well as angular distributions of the W bosons produced. Measurements at LEP 2 considerably reduced the possibilities for the so-called anomalous couplings since the results agree very well with the predictions of the Standard Model. The amount of the collected data considerably reduced possible statistical fluctuations, so currently emphasis is put on the reduction of systematic uncertainties.

Probably the most elegant scenario that provides masses for the elementary particles (e.g. for quarks or for the carriers of the weak interactions) is spontaneous symmetry breaking. All variations of the scenario require the existence of at least one scalar particle - the so-called Higgs boson. With higher beam energy at LEP 2 it is now possible to search for a heavier Higgs boson than at the former LEP 1 collider. Nevertheless, up to now the searches have not confirmed the existence of a Higgs boson. This sets a lower limit for the neutral Higgs boson mass, at present around 90 GeV/c^2. Several extensions of the Standard Model also introduce charged Higgs scalars but, as in the case of the neutral Higgs boson, no evidence of their existence was found in 1998 DELPHI data. Lower limits for their masses vary between 55 and 65 GeV/c^2 and depend heavily on the theoretical model used to connect their production cross-section and the hypothetical mass of $H^{\pm}$.

Apart from direct searches it is also possible to determine the Higgs boson mass m_H from indirect observations. The exchange of Higgs bosons plays a sizeable role in the perturbative calculations of higher order corrections to many of the processes that are accessible at LEP energies. We can make use of the precise measurement of the $W^{\pm}$ mass or angular distributions of the Z^0 decay products, recorded at LEP 1 in years 1990-1995. For example, by comparing forward-backward asymmetries of quarks and leptons from Z^0 decays to Standard Model calculations it is possible to predict an m_H upper limit of 450 GeV/c^2_0. We prepared a new method for measuring the forward-backward asymmetry in $Z^0 \rightarrow b\bar{b}$ decays by tagging the b-quark flavour with fast charged kaons arising from the b → c → s quark transitions. The analysis profits from the fact that in Z^0 decays a quark is always produced together with an antiquark of the same flavour. This allows for calibration of the most important detector components with the measured data, a lower sensitivity to the simulated processes, and thus for a more accurately measured asymmetry. The aim of this work is to combine the results obtained with previous measurements and thus to set more stringent limits on m_H.

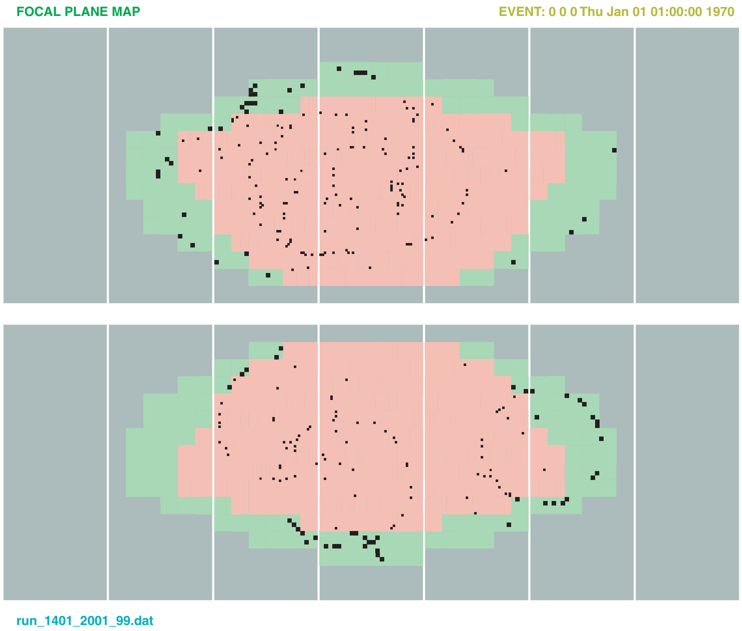

Figure 3: On-line display of a typical Ring Imaging Cherenkov event from the HERA-B experiment at DESY, Hamburg. Upper and lower arrays of photomultipliers are shown: the optical system is split in the plane of the HERA proton beam, sending Cherenkov photons to either detector array. The photomultiplier hits are represented as black squares. The inner region (pink) is covered by 16-channel photomultipliers, with coarser 4-channel tubes outside (light-green region). There are 26816 single-photon detector channels in the system

HERA-B Collaboration

The Ring Imaging Cherenkov counter (RICH) for the HERA-B experiment was fully installed in spring 1998. Prior to the installation, each of the 2250 multianode photomultipliers was quality assessed, and its working point determined. After initial stand-alone tests the full system was commissioned in its final set-up by using charged tracks as produced in interactions of high energy protons with wire targets in the halo of the proton beam (Fig. 3). The system was very stable up to the highest interaction rates (40 MHz). By using the information on the cluster position in the electromagnetic calorimeter behind the RICH counter to identify high energy electrons and determine their direction, corresponding rings on the photon detector plane were found.

Development and application of detectors

In the detector development laboratory, applications of high-energy physics techniques to other fields, notably medicine and environmental monitoring, are taking place. Silicon microstrip detectors were used in a test set-up for digital X-ray imaging. The study of the system's quantum efficiency in the X-ray region showed efficiencies as high as 85 % with proper design and fabrication. The system is planned for digital mammography as a substitute for screen-film, and images of a standard breast phantom were therefore made and evaluated. The delivered dose of X-ray radiation was measured. Measurements show the possibility of a significant dose reduction per exposure, due to the excellent efficiency of silicon detectors.

Some outstanding publications in the past three years

1. **CPLEAR Collaboration: A.Filipčič, I.Mandić, M.Mikuž, D.Zavrtanik, et al. (72 authors), First direct observation of time-reversal non-invariance in the neutral-kaon system, Phys. Lett. B444, 1998, 43-51**
2. **DELPHI Collaboration: V.Cindro, B.Eržen, B.Golob, T.Podobnik, S.Stanič, D.Zavrtanik, D. Žontar et al. (544 authors), Measurement and interpretation of the W-pair cross-section in e^+e^- interactions at 161 GeV, Phys. Lett. B397, 1997, 158-170**
3. **P.Križan, S.Korpar, M.Starič, A.Stanovnik, M.Cindro, G.Močnik, D.Škrk, M.Zavrtanik, A.Bulla, E.Michel, P.Weyers, W.Schmidt-Parzefall, T.Hamacher, R.Schwitters, The RICH detector for HERA-B, Nucl. Instr. and Meth. in Phys. Res. A371, 1996, 295-299**
4. **V.Cindro, G.Kramberger, M.Mikuž, D.Žontar, Bias-dependent annealing of radiation damage in neutron-irradiated silicon p^+-n-n^+ diodes, Nucl. Instr. and Meth. in Phys. Res. A419, 1998, 132-136**
5. **DELPHI Collaboration: V.Cindro, B.Eržen, B.Golob, T.Podobnik, S.Stanič, D.Zavrtanik, et al. (545 authors), Search for charginos, neutralinos and gravitinos at LEP, Eur. Phys. J. C1, 1998, 1-20**