The Discovery of $B\overline{B}$ mixing

Walter Schmidt-Parzefall
Universität Hamburg

Welcome to the celebration of the 20th anniversary of the discovery of $B\overline{B}$ mixing, achieved by ARGUS in 1987. What made this discovery possible, D. Cassel explained in his talk on the occasion of the termination of the ARGUS experiment:

> Have a better detector that can "see all"
> Have excellent physics analysis software
> Have excellent physics ideas and follow them
> Have a little bit of luck.

This is also the outline of my talk.

1 The ARGUS Detector

Everything began in 1977. At DESY the new e^+e^- storage ring PETRA was successfully brought into operation. Moreover, the DESY director H. Schopper decided, that research at the old storage ring DORIS should be continued with a new detector. For this purpose he set up a new research group at DESY and invited for the formation of an international collaboration to work at DORIS.

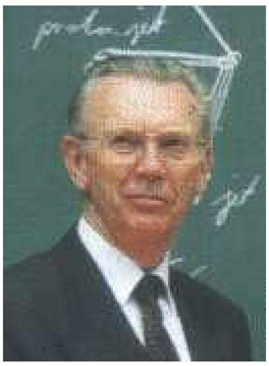

Figure 1: H. Schopper

Also in 1977 the Υ and thus the 5th quark, the b-quark was discovered by L. Lederman and his group at FNAL. Consequently, it was decided to upgrade the energy of DORIS in order to produce the Υ states by e^+e^- collisions. The new DORIS collaboration obtained the DASP detector, since its former owners had quit. The DASP detector gave very valuable experience on experimentation in the e^+e^- environment and it immediately provided important new physics results from the upgraded DORIS. The two lowest Υ states, the $\Upsilon(1S)$ and $\Upsilon(2S)$ were, together with PLUTO, found at DORIS and their parameters were precisely measured in 1978.

The main task, however, was to design a new detector for DORIS. It received the name ARGUS, the name of the hero of Greek mythology having many eyes so that he would see everything. But the actual meaning underlying this name was only found later, in a physicists wife point of view. She said:

"Alle Richtigen Genies Unter Sich".

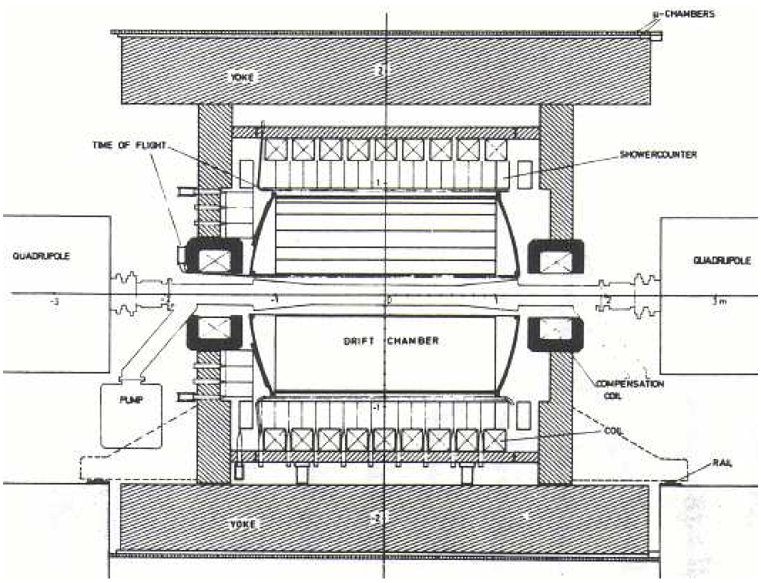

Figure 2: The first version of the ARGUS detector

H. Schopper fully supported the project. He emphazised: What counts is that the new detector is competitive. In order to reach this goal, money was not an issue. But then he left to become director general of CERN. Now we had to learn the art of getting hold of sufficient support.

For the design criteria of the new detector the recently constructed detectors at PETRA and PEP were very instructive and were studied in detail. In order to present my first detector design, a workshop was held at DESY on

10. 11. 1977. This first version of ARGUS shown in Fig.2 had already many features of the final design.

It has a homogenous structure over a large range of solid angle. Various magnetic field configurations had been studied, but it turned out that the classical solenoid field had the best properties. In order to avoid delays, a normal conducting magnet coil was chosen. Since the detector performance is improving by a high magnetic field, the magnetic field was made as high as achievable by a normal conducting coil. The magnetic field of the detector thus defined, was 0.8 T.

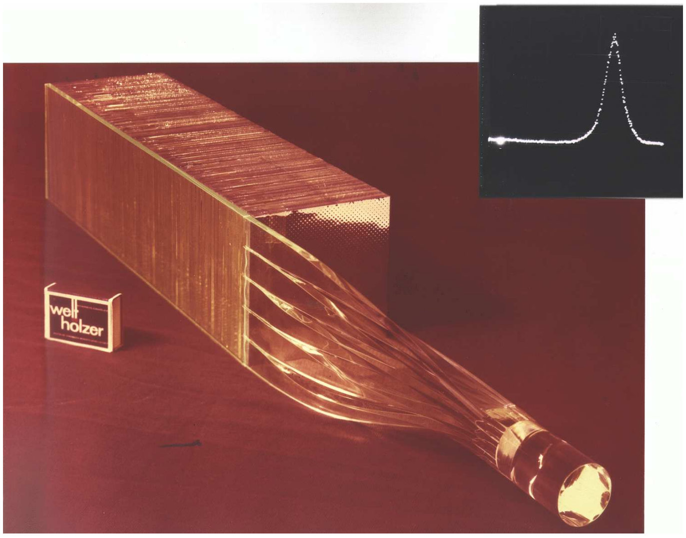

Figure 3: Prototype for the ARGUS shower counters, consisting of a lead scintillator sandwich read out by a wavelengh shifter bar. Also shown the energy distribution for 1 GeV electrons

The copper coil producing this field is too thick so that no particles other than muons can be detected behind it. Thus the electromagnetic calorimeter for the detection of γ-rays and electrons had to be placed inside the magnetic field volume in front of the coil. Fortunately, a new type of shower counter suited for this purpose had been invented just recently by W.B. Atwood. It consists of a lead-scintillator sandwich read out by a wavelength shifter bar doted with BBQ. The light is concentrated into an area, which is small enough so that it can be transported by lightguides through slits between the coil segments to the field free region behind the coil, where photo-multipliers can work. A first prototype shown in Fig.3 was quickly made at DESY and tested at a test-beam. It showed an even better energy-resolution than obtained by the inventor. In the final detector an energy resolution of

$$\sigma_E/E = \sqrt{7^2 + 8^2\,\mathrm{GeV}/E}\ \%$$

was obtained. No e^+e^--detector at that time had a calorimeter with a better energy resolution.

This first design of ARGUS had as the central track detector a copy of the Jet-chamber of JADE. Since particle identification is essential for B-physics, its appealing feature was, that it combined momentum determination with a measurement of dE/dx for particle identification.

2 Forming the ARGUS collaboration

Building up the collaboration worked mainly by personal relations.

The first ally was D. Wegener of the Universität Dortmund. We had met many years before as students in the Göttingen Physics Institute and than worked together in Karlsruhe from where we did the DESY Experiment F23. Then we met again at CERN from where we made tours to the famous restaurants of Burgundy, enjoying life together.

Next, K. Schubert from the Universität Heidelberg joined. We had met at CERN and worked together in the CHOV collaboration at the ISR.

The director for research G. Weber knew G. von Dardel of Lund University in Sweden. Consequently, L. Jönsson joined the collaboration.

DESY director H. Schopper had worked in Russia before and by these contacts he arranged a collaboration with ITEP Moscow, which turned out very fruitful.

Finally, C. Darden from South Carolina University joined. He had just recently married a German wife and therefore spent his sabbatical at DESY, were he got interested in the project.

The formation of an efficient research group was strongly supported by G. Weber, who helped us a lot to get started.

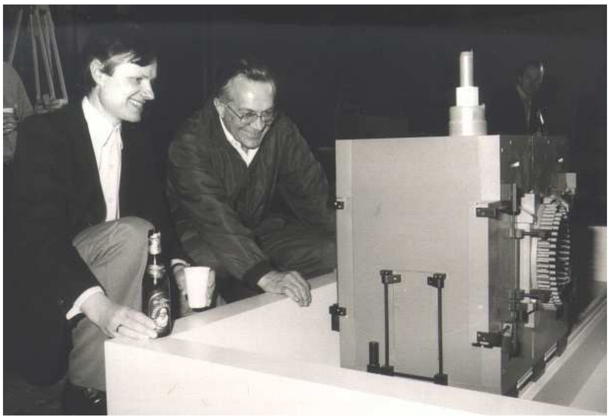

Figure 4: The author and G. Weber with a model of the ARGUS detector

3 The proposal version of ARGUS

Together with the new DESY group, these five groups worked out the proposal
ARGUS, A New Detector for DORIS
which was submitted in October 1978 and approved on 5. 7. 1979.

The proposal version of the detector [1] is shown in Fig.5 The performance of such a detector improves with increasing size. As a limit the existing pit around the interaction region of DORIS was taken. Thus no time was lost for enlarging the pit and changing the foundations of the storage ring.

The main new feature of the proposal version of ARGUS was a new central driftchamber. It had turned out that the charge division method used by JADE for the measurement of the longitudinal track coordinate, needed a gas-gain too high for good dE/dx resolution and had the disadvantage of doubling the front-end electronics.

In order to avoid these problems, I worked out a novel driftchamber design [2], which is capable of measuring dE/dx, but uses small angle stereo to measure the longitudinal coordinate. The driftchamber consists of 5940 drift-cells with an approximate quadratic shape, as Fig.6 shows. They are arranged in 36 layers. Every second layer is tilted by a stereo angle. In such a stereo layer the projection of a sense wire, seen from the side, forms a hyperbola. For a sufficiently constant gas-gain over the whole sense wire, the maximum deviation of the hyperbola from a straight line was set to 1 mm. The stereo angle of each layer was thus defined. It increases with radius and gives a good space-resolution. The size of the drift-cell of 18 mm was chosen because it fully

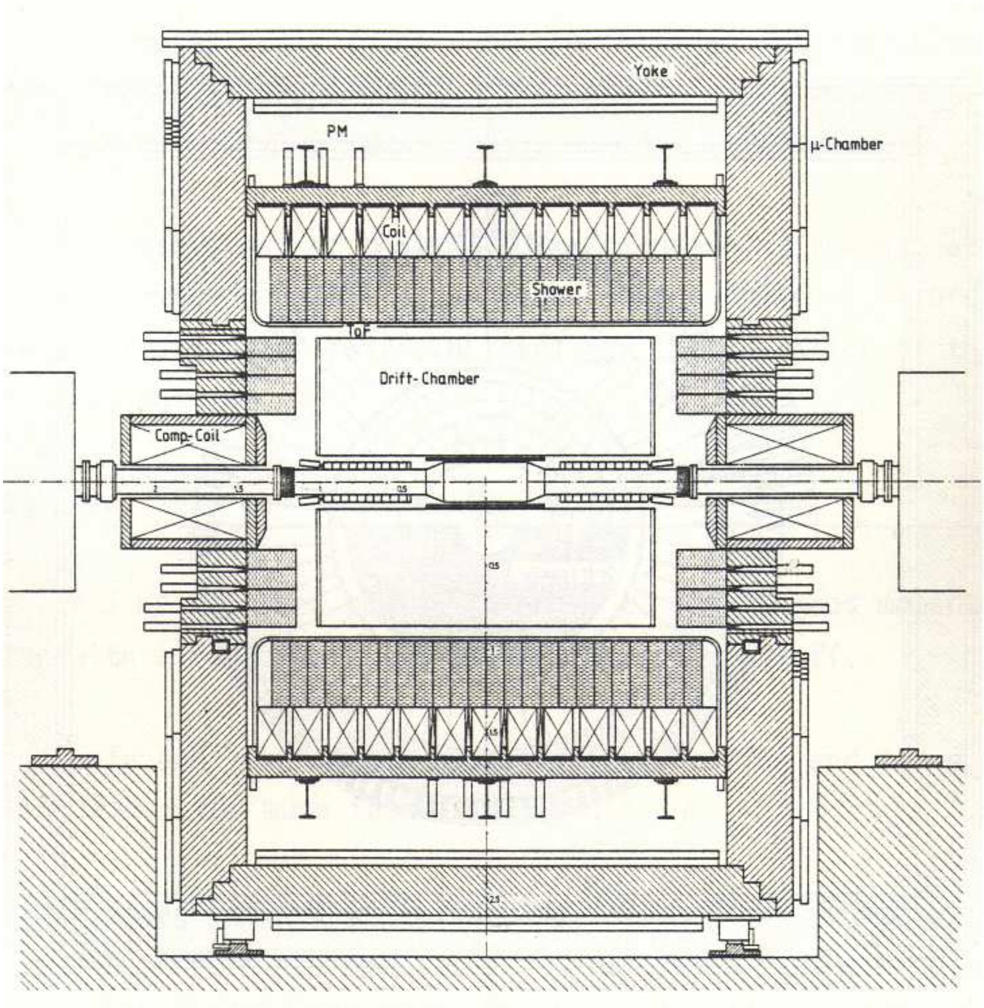

Figure 5: The proposal version of the ARGUS detector

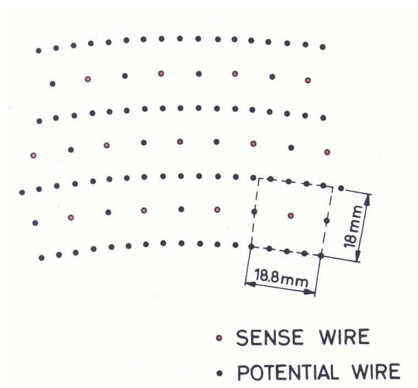

Figure 6: The cell structure of the ARGUS driftchamber

exploits the dE/dx information obtainable from the counting-gas. The price to pay for the excellent performance of this design was that 24588 potential wires had to be strung. The proposal version had even 30804 potential wires. But an optimisation performed at ITEP Moscow showed that this number could be reduced.

It was the opinion of many of the experts of that time, that it was crazy to try to build such a chamber. But finally it worked very well.

4 Enlarging the collaboration

The collaboration was not yet strong enough to manage. But it grew.

N. Kwak from Kansas University, who had already worked with us in CHOV at CERN joined together with R. Ammar and R. Davis.

Next a very strong team from the IPP Canada joined. It consisted of
P. Patel and T.S. Yoon, Montreal
J. Pentice and W. Frisken, Toronto
K. Edwards, Ottawa

Finally, the collaboration was completed by the teams of
G. Kernel, University of Ljubljana and
H. Wegener, Universität Erlangen.

In total the collaboration consisted of about 80 scientists. It had no committees, no boards, no panels. Nevertheless, the collaboration worked very well. Probably because it was an unusual collection of brilliant people.

5 The luminosity upgrade of DORIS

By 1980 a very important upgrade of DORIS [3] was initiated. H. Nesemann and K. Wille were made responsible for DORIS. It was their initiative to work out an upgrade project in order to make DORIS competitive with CESR, which was under construction at Cornell and was also planning to do B-physics. The basic idea of this upgrade was to increase the luminosity of DORIS by mini-beta quadrupoles positioned close to the interaction point. This appeared impossible, since the quadrupoles had to be placed inside the ARGUS detector, where the high magnetic detector field would prevent them from operating properly. But the expected luminosity increase by a factor of ten was an offer, which one

Figure 7: K. Wille

simply could not reject. Therefore, I came up with an arrangement of compensating coils to protect the mini-beta quads against the detector field. This scheme was checked by K. Wille and found to be satisfactory. Fortunately, the director of research at that time, E. Lohrmann strongly supported this idea, so that it was approved by DESY.

Figure 8: E. Lohrmann

The official decision to perform the luminosity upgrade of DORIS was prepared at a workshop on 10.02.1981. It was attended by E. Bloom, the spokesman of the Crystal Ball experiment at SLAC. He stated, that if this upgrade really were made as proposed, he would bring the Crystal Ball experiment to DESY. That a scientific team with such a high reputation from the United States would come to DESY, was sufficient motivation for DORIS to be essentially rebuilt at the highest standards of accelerator technology. The good thing for ARGUS was, that we got a marvelous machine. But since Crystal Ball was given priority, we had to wait for some years until their research programme was finished, before we could start with the ARGUS research programme.

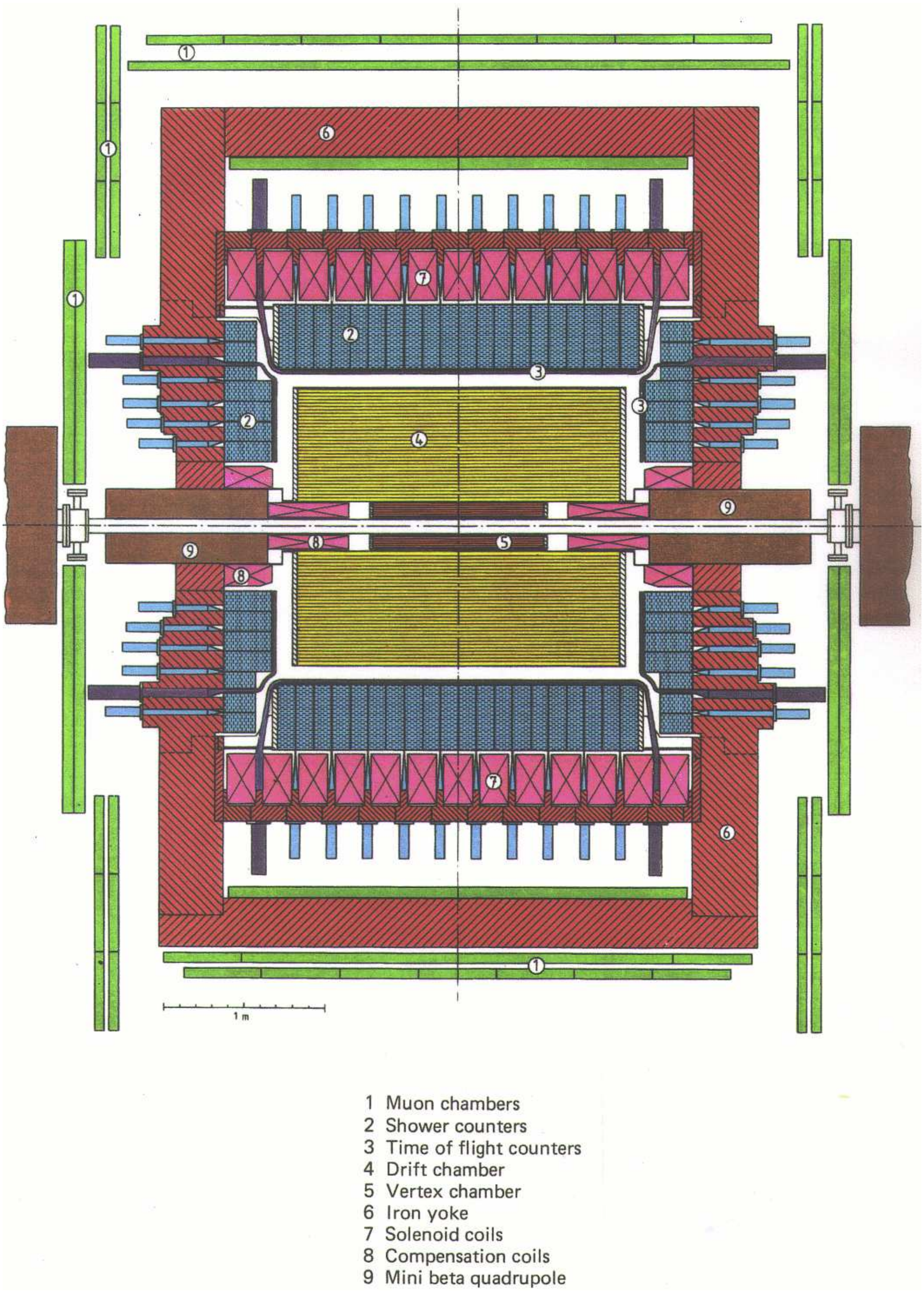

Figure 9: The final version of the ARGUS detector

The luminosity upgrade required a change of the detector design in order to accommodate the mini-beta quadrupoles. Thus, the layout of ARGUS was again modified and received its final shape [4] as displayed in Fig.9. This design turned out to be quite competitive.

6 Building the detector

Now the task of the participating institutes was to build the detector. In addition to the infrastructure and the magnet, the following components were contributed by the DESY group, listed together with the responsible persons: the driftchamber E. Michel, the track-finder trigger H.-D. Schulz and the data acquisition R. Wurth.

Figure 10: L. Jönsson

The driftchamber design really was at the edge of technical possibilities. No German company could be found, which was prepared to drill the 60000 precision holes into the end-plates of the driftchamber. Finally, L. Jönsson found a company in Sweden, which did the job under his supervision. A picture of the drift-chamber under construction, with light reflected from the wires is shown in Fig.11 .

D. Wegener and his team of the Universität Dortmund took the responsibility for the development and the production of the shower-counters [5]. The barrel consisted of 1280 and the two end-caps of 480 counters. Thus, an enormous job had to be managed. Part of the shower-counters ready for installation are shown in Fig.13 .

The time-of-flight system [6] was contributed by K. Schubert and his group from the Universität Heidelberg. It consisted of 64 barrel counters and 48

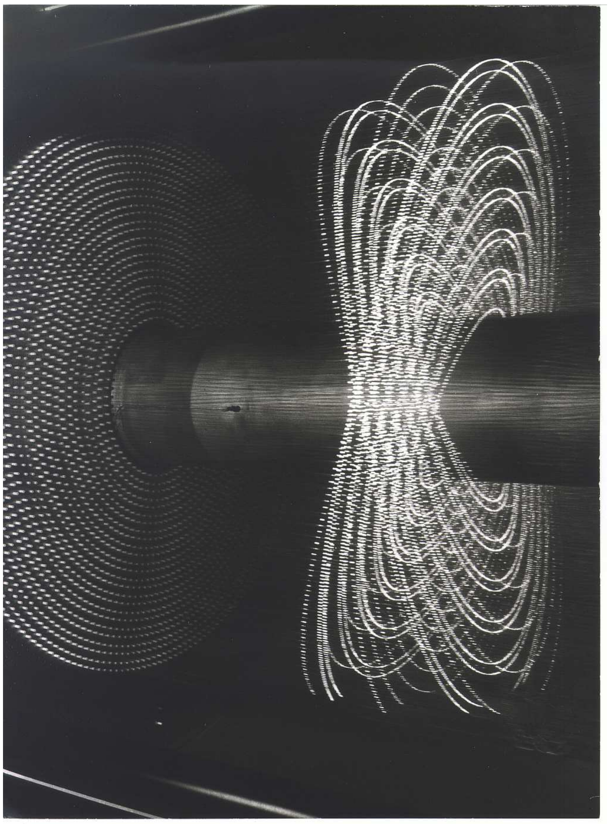

Figure 11: The central driftchamber under construction.The light reflected from the wires indicates the complex cell structure.

Figure 12: D. Wegener

end-cap counters and reached the excellent time resolution of 220 ps.

The detector was surrounded by two layers of muon chambers, [7] which were contributed by ITEP Moscow. They consisted of 1744 aluminum tubes.

Figure 13: The shower counters ready for installation

Figure 14: K. Schubert

The outer layer covered a solid angle of $0.87 \times 4\pi$.

The vertex-driftchamber [8] located inside the central driftchamber was contributed by IPP Canada. Actually, during the data taking period of ARGUS three versions were built and installed, with gradually improving performance. The second version had 594 hexagonal driftcells. It provided a significant improvement of the momentum resolution. The combined momentum resolution of both driftchambers was very good and reached

$$\sigma(p_T)/p_T = \sqrt{0.01^2 + (0.006\, p_T/(\mathrm{GeV/c}))^2}.$$

In 1982 the commissioning of the detector took place. After the usual initial troubles, to our surprise, the detector worked perfectly. Each of the collaborating institutes had delivered its detector component, completely meeting the specifications.

It turned out, that the particle identification power of the time-of-flight sys-

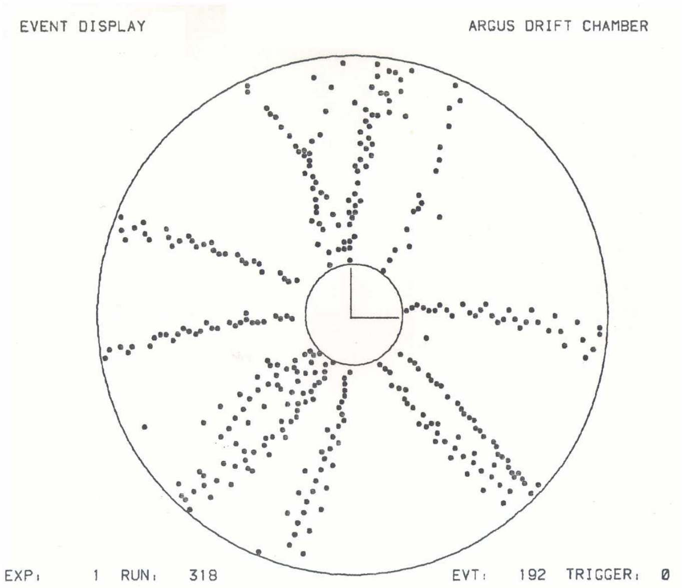

Figure 15: The online display of one of the first events recorded

tem and of the dE/dx measurement by the driftchamber were equally good. Both reached a π-K separation of $3\,\sigma$ up to 750 MeV. Thus, always both techniques were used, resulting in improved particle assignments.

7 Running the Experiment

Data taking started in fall 1982. The online display of one of the first events recorded is given in Fig.15. It shows the three stereo views of the central driftchamber. The data are remarkably clean and complete.

A reconstructed typical event, showing only the longitudinal wires is displayed in Fig.16. This picture shows the excellent pattern-recognition capabilities of the ARGUS driftchamber. Close tracks and crossing tracks are clearly recognized.

Most of the event-reconstruction software of ARGUS has been written by H. Albrecht. In addition, in close connection with H. Schröder, at that time the ARGUS physics coordinator, he developed an analysis language called KAL. This language served as a user interface to the reconstructed data. It was used by all people doing data analysis.

After some time it was free of bugs, so that ARGUS produced very re-

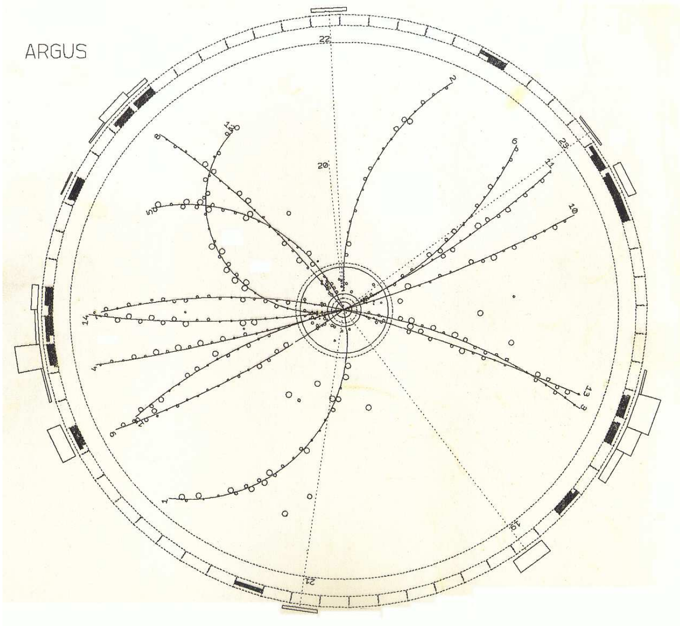

Figure 16: A typical event after reconstruction showing the excellent pattern-recognition capabilities of the ARGUS driftchamber

Figure 17: H. Albrecht

liable results. The large number of publications was only possible through this analysis language. It allowed to concentrate on the physics issues, not beeing distracted by the always repeating difficult technical aspects of data-calibration and data-reconstruction.

The responsibility for good data quality stayed over the whole running time of the experiment with the institute, which originally contributed the hardware. Due to this clear responsibility structure, the data quality was always close to perfect.

After the termination of the Crystal Ball experiment in 1985, ARGUS could begin with its own research programme. It concentrated on the weak interaction of the 5th quark, the b quark. Also the Υ states, the heavy lepton τ, the charmed quark and $\gamma - \gamma$-physics were important research topics of ARGUS. But the most important topic was b-physics. Only CLEO at Cornell and ARGUS at DESY had the facilities to do this research. Both groups worked in a fruitful competition and and in most cases confirmed each other.

By 1987 the number of B-mesons collected by ARGUS was 176 000, while CLEO had already collected 263 000 B-mesons. However, the overall efficiency of ARGUS was higher than the efficiency of CLEO, what compensated for the lower number of recorded events.

8 b-Physics

The starting point for the study of the weak interaction of the b-quark is the $\Upsilon(4S)$ state, which is a $b\bar{b}$ bound state. It is produced by e^+e^- annihilation as shown in Fig.18. Its mass is just high enough, that it can decay into a pair of B-mesons. The B-mesons produced are either neutral or charged. Their quark contents is $B^0 = \bar{b}d$ and $B^+ = \bar{b}u$.

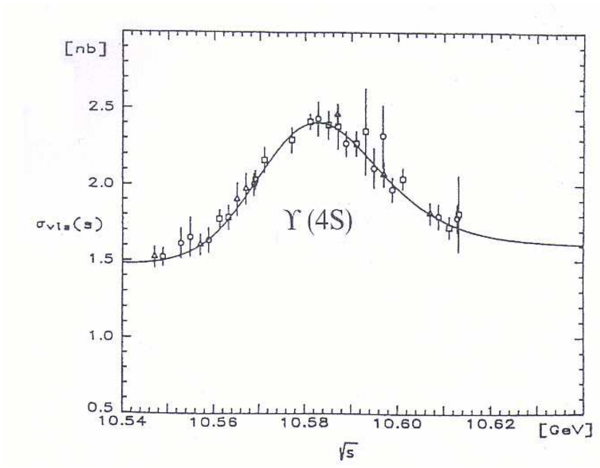

Figure 18: The $\Upsilon(4S)$ state produced by e^+e^- annihilations. It decays into a pair of B-mesons as a starting point for the study of the weak interaction of the b quark

Thus the starting reaction is, expressed by mesons

$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0 \text{ or } B^+B^-$$

or expressed by quarks

$$e^+e^- \rightarrow \quad \bar{b}b \quad \rightarrow \bar{b}d\ \bar{d}b \text{ or } \bar{b}u\ \bar{u}b$$

The b-quarks thus produced allow to study their weak interaction. It proceeds by the transition of a quark i into a quark k via emission or absorption of a $W^\pm$ boson.

$$q_i \rightarrow q_k + W^\pm$$

The couplings of any unlike charged pair of quarks i, k to the $W^\pm$ boson

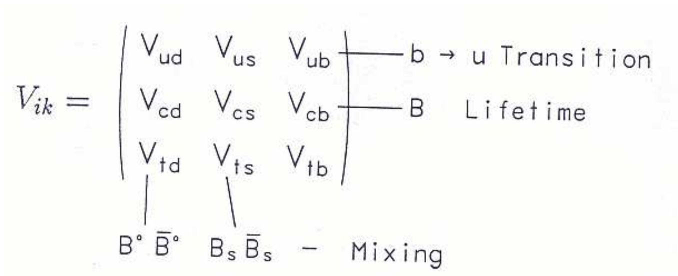

Figure 19: The CKM matrix. The elements involving the 3rd generation of quarks are subject of b-physics.

are proportional to amplitudes V_{ik} which form the elements of the Cabibbo-Kobayashi-Maskava (CKM) matrix. These parameters represent an arbitrary input into the Standard Model. They have to be determined experimentally.

The CKM matrix elements involving the 3rd generation of quarks are essentially the subject of B-meson physics as summarized in Fig.19.

$\mid V_{ub} \mid$ is given by the branching ratio for the transition $b \rightarrow u$.
It was discovered by CLEO and ARGUS in 1989.
$\mid V_{cb} \mid$ is derived from the lifetime of the B-mesons.
$\mid V_{td} \mid$ and $\mid V_{ts} \mid$ are accessible via $B^0\overline{B}^0$ and $B_s\overline{B}_s$ mixing.
$\mid V_{tb} \mid$ is close to unity.

9 $B\overline{B}$ Mixing

B^0-mesons may transform into their antiparticles through the box diagrams as shown in Fig.20. Such a box diagram is of special interest, since it is dominated by the exchange of the heaviest particle, contributing to the loop.

A similar box diagram for the K^0-meson played already a major role in particle physics. It lead to the prediction of the charm-quark, which was required to make the loop integral finite.

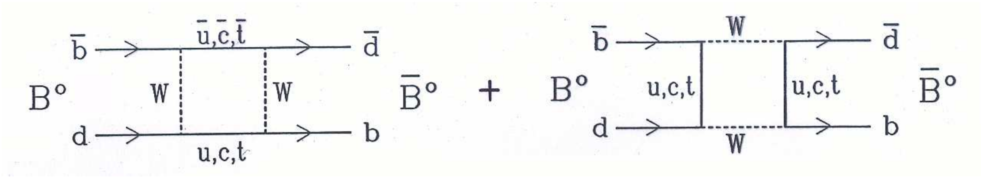

Figure 20: The box graphs implying the transition of a B^0-meson into its antiparticle

Since B^0-mesons transform into their antiparticles, the states

$$< B^0 > \quad \text{and} \quad < \overline{B^0} >$$

are not mass eigenstates. The two states mix and form the stationary mass eigenstates

$$\frac{1}{\sqrt{2}} < B^0 + \overline{B^0} > \quad \text{and} \quad \frac{1}{\sqrt{2}} < B^0 - \overline{B^0} >,$$

which differ in mass by an amount ΔM.

Assuming that the two mixed states have equal lifetime and total width Γ, the quantum mechanics of such a two state system leads to a simple formula for its time evolution. For a system which is entirely B^0 at time zero, the intensity to find it in a $\overline{B^0}$ state is

$$I_{\overline{B^0}}(t) = \frac{1}{2}\,\mathrm{e}^{-\Gamma t}(1 - \cos \Delta M\, t), \qquad I_{B^0}(0) = 1.$$

This relation shows an oscillation term, where ΔM is the oscillation frequency. There are two competing reactions: A B^0-meson can either decay with decay width Γ or transform into its antiparticle with frequency ΔM. The mixing parameter x defined as

$$x = \frac{\Delta M}{\Gamma}$$

is the relative strength of the two reactions. In order to present the results of time integrated experiments, the mixing parameter r has been introduced, which is defined as the rate to find a particle originally produced as a B^0-meson at the time of decay as a $\overline{B^0}$-meson, over the rate to find it as a B^0-meson. On the $\Upsilon(4S)$ where B-meson pairs are produced in a correlated state r is related to x by

$$r = \frac{BR(B \to \overline{B} \to \overline{X})}{BR(B \to X)} = \frac{x^2}{2 + x^2}.$$

Thus in essence, a measurement of r represents a determination of ΔM.

By 1987 the theoretical expectations predicted a substantial mixing, $r \approx 1$ for the $b\overline{s}$-meson and a very small mixing for the $b\overline{d}$-meson.

The experiments on $B\overline{B}$ mixing used reactions, where primarily $B\overline{B}$ pairs are created. Through mixing a B-meson transforms into its antiparticle, which leads to $B\,B$ or $\overline{B}\,\overline{B}$ pairs. Observation of such like-kind B-meson pairs is then taken as evidence for mixing. Instead of a complete reconstruction of B-mesons, semi-leptonic B decays can be used. This allows one to tag B-mesons with the lepton charge, which is correlated with the charge of the decaying b-quark.

$$B^0 \to \ell^+ X \qquad \overline{B^0} \to \ell^- \overline{X}.$$

Thus the observation of like-sign lepton pairs originating from B-meson decays is evidence for $B\overline{B}$ mixing. However, leptons also originate from charm and strange decays. Clearly this method requires a very good understanding of the background.

Upper limits on $B\overline{B}$ mixing were already reported by the collaborations CLEO, MARK II and JADE [9]. By 1986, the UA1 collaboration reported a 3 standard deviations excess of like-sign muon pairs [10], which was generally interpreted as $b\overline{s}$ mixing and no great surprise.

The major breakthrough for the observation of $B\overline{B}$ mixing was achieved by the ARGUS collaboration in 1987. For this discovery two independent lines of analysis were followed, the search for like-sign lepton pairs and the reconstruction of semi-leptonic B-meson decays.

Since ITEP Moscow had the experts on leptons, in early 1987 I asked a student from ITEP to look into like-sign lepton pairs. I told him: "Theorist say that it is very important, but you will see nothing." After some time, the student presented his result. He had found no like-sign lepton pairs. Actually, he had invented very innocently looking smart cuts and killed all candidates in order to arrive at the expectation.

I was content to learn that ARGUS had very little background and a high sensitivity for this reaction. But CLEO had just recently published a limit on $B\overline{B}$ mixing. Due to this competition, the ARGUS collaboration decided, that our much better limit should also be published. Thus a paper was quickly written and submitted to the Journal.

The other line of analysis proceeded via the reconstruction of B-mesons.

Figure 21: H. Schröder

H. Schröder had developed a method to reconstruct semi-leptonic B decays. The basic idea of this method was to compute the mass of the unseen neutrino from the kinematic variables of the other decay products of the B-meson, and require this mass to be close to zero.

For the decay $B^0 \to D^* \ell \nu$ the expression for the neutrino mass M_ν is

$$\begin{aligned} M_\nu^2 &= (E_B - E_{D^*} - E_\ell)^2 - (\mathbf{p}_B - \mathbf{p}_{D^*} - \mathbf{p}_\ell)^2 \\ &\approx (E_{\text{Beam}} - E_{D^*} - E_\ell)^2 - (\mathbf{p}_{D^*} + \mathbf{p}_\ell)^2, \end{aligned}$$

where Schröders trick was, to exploit $E_B = E_{\text{Beam}}$ and $\mathbf{p}_B \approx 0$.

The distribution of neutrino masses thus obtained is shown in Fig.22.

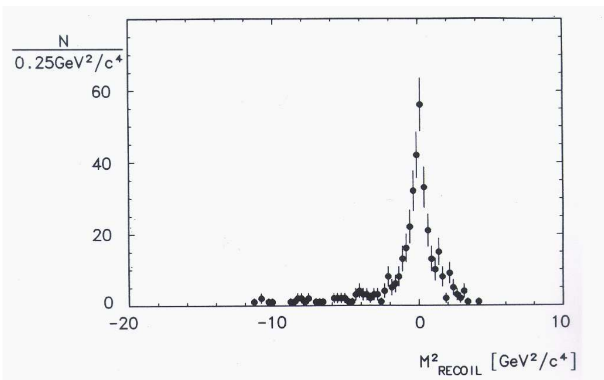

Figure 22: The distribution of the neutrino mass squared for reconstructed semi-leptonic decays $B \to D^* \ell \nu$

H. Schröder studied these reconstructed events in detail. By early 1987 he discovered a few events, having the signature of $B\overline{B}$ mixing and showed them to me. However, at that time the statistics were still too small to arrive at a quantitative result.

About two weeks after our paper with the limit on $B\overline{B}$ mixing had been sent away, a big delegation of ARGUS people came into my office. Among the people entering were H. Schröder, Yu. Zaitsev, A. Golutvin and D. MacFarlane. They informed me, that after new data had become available and the old data had been reprocessed, many like-sign lepton pairs had been found.

Figure 23: Yu. Zaitsev and A. Golutvin

Thus our paper was definitely wrong. I agreed to write to the Journal and to withdraw the paper. In addition, the already printed DESY red reports were collected, just in time before they were mailed.

On this meeting everybody felt that very probably we had made a discovery. In order to work it out in detail, the necessary work was distributed. Yu. Zaitsev agreed to supervise the ITEP people around and to work on lepton pairs. H. Schröder agreed to continue his work on reconstructed B-mesons and D. MacFarlane agreed to work out the lepton background from other sources.

Figure 24: D. MacFarlane

Soon the final result was worked out. H. Schröder had found his golden event, shown in Fig.25. Instead of the usual $B\overline{B}$-meson pair it contains two B^0-mesons each decaying via $B^0 \to D^{*-}\mu^+\nu$ and demonstrates explicitely that $B^0\overline{B^0}$ mixing occurs.

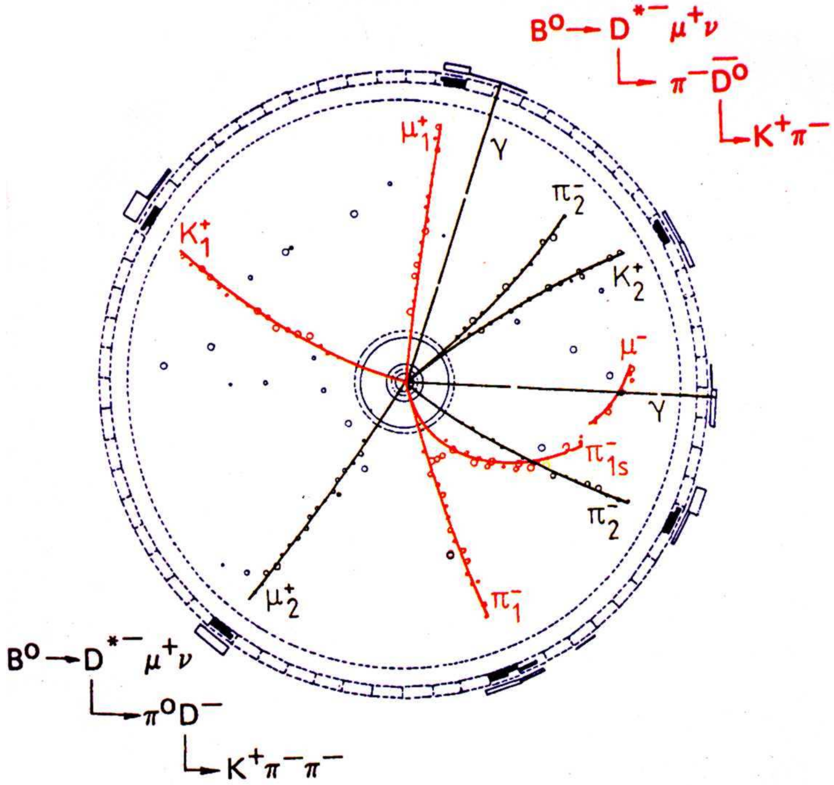

Figure 25: The golden event found by H. Schröder. It shows the reaction $\Upsilon(4S) \to B^0\overline{B^0} \to B^0B^0$, which is evidence for $B\overline{B}$ mixing.

In addition, H. Schröder analysed events containing a B-meson and a lepton. Taking all reconstructed B^0-mesons available, which decay like $B^0 \to D^*\ell\nu$ or $B^0 \to D^*n\pi$, and asking for an additional lepton with a momentum above 1.4 GeV/c, he found 5 ± 0.9 candidates for mixing together with 23 ± 2.5 normal events. The advantage of this method is its low background rate. The mixing parameter r obtained was

$$r = \frac{N(B^0\ell^+) + N(\overline{B^0}\ell^-)}{N(B^0\ell^-) + N(\overline{B^0}\ell^+)} = 0.20 \pm 0.12.$$

Yu. Zaitsev presented his results on lepton pairs using leptons with momenta above 1.4 GeV/c. He studied both electrons and muons and obtained three mixing rates, which are consistent with each other.

$$r_{ee} = 0.17 \pm 0.19, \quad r_{\mu\mu} = 0.19 \pm 0.16, \quad r_{e\mu} = 0.28 \pm 0.14.$$

The combined like-sign lepton pair result is

$$r = 0.22 \pm 0.09.$$

This result together with the evidence from B^0-meson lepton combinations gives the ARGUS result

$$r = 0.21 \pm 0.08.$$

Before publishing this result, the question was then raised whether this surprisingly large rate of $B^0\overline{B^0}$ mixing was consistent with the Standard Model and its parameters, or whether new physics was required to explain it. Since the Standard Model works so well, I would have felt uneasy to publish a result inconsistent with the Standard Model.

In the Standard Theory, $B^0\overline{B^0}$ mixing is described by the box graph, Fig.20. From an analysis of the corresponding box graph of the K^0 system, M.K. Gaillard and B.W. Lee [11] had successfully predicted the mass of the c quark. Similarly $B^0\overline{B^0}$ mixing is sensitive to the t quark mass.

The amplitude of a box graph is divergent, unless the contributions of the individual quark exchange amplitudes cancel each other at high momentum transfer. For this cancelation, called the GIM mechanism [12], to be realized, the CKM elements must fulfill

$$V_{bu}^* V_{ud} + V_{bc}^* V_{cd} + V_{bt}^* V_{td} = 0.$$

This relation is guaranteed by the unitarity of the CKM matrix.

The oscillation frequency ΔM is then given by

$$\begin{aligned} \Delta M &= < B \mid j_\mu j^\mu \mid B > \\ &\times \int_0^\infty \frac{k^4}{8\pi^2} \left(\frac{V_{bu}^* V_{ud}}{k^2 - m_u^2} + \frac{V_{bc}^* V_{cd}}{k^2 - m_c^2} + \frac{V_{bt}^* V_{td}}{k^2 - m_t^2} \right)^2 \left(\frac{g^2}{k^2 - m_W^2} \right)^2 \mathrm{d}k^2. \end{aligned}$$

Mixing can only occur, if the two quarks in the B^0-meson come close together. This probability is contained in the term

$$< B \mid j_\mu j^\mu \mid B > = \frac{4}{3}\, m_b B_B f_B^2.$$

Besides the b quark mass m_b, it depends on a bag factor B_B and the B^0-meson decay-constant f_B.

The loop integral is easily evaluated, if the masses of the lighter quarks are set to zero, an approximation, which is well justified. The W-exchange term simply gives the Fermi coupling constant G_F^2 for $m_t^2 << m_W^2$. For a larger top quark mass a slowly varying correction function $A(z)$ has to be introduced

$$A(z) = \frac{1}{4} + \frac{9}{4(1-z)} - \frac{3}{2(1-z)^2} - \frac{3z^2 \ln z}{2(1-z)^3}.$$

Finally a small QCD correction η_{QCD} must be applied. Thus the mixing frequency is given by [13]

$$\Delta M = \frac{G_F^2}{6\pi^2} m_b B_B f_B^2 \mid V_{bt}^* V_{td} \mid^2 m_t^2 A\left(\frac{m_t^2}{m_W^2}\right) \eta_{QCD}.$$

Since the observed mixing rate r is related to ΔM by

$$r \approx \frac{1}{2}\left(\frac{\Delta M}{\Gamma}\right)^2,$$

the observed mixing rate r is proportional to the fourth power of the top quark mass which, however, was not known at that time. But our result on r allowed to obtain a lower limit for m_t.

In order to estimate the unknown parameters of the B-meson in the expression for ΔM, I assumed that the QCD of a B-meson is not much different from the QCD of the K-meson. In both cases there is a heavy quark surrounded by a light quark. Thus naively I set

$$\sqrt{B_B \, \eta_{QCD}} \, f_B = f_K = 160 \, \text{MeV}.$$

The unknown CKM elements by 1987 were already constrained within

$$\mid V_{td} \mid = 0.002 \text{ to } 0.018, \qquad \mid V_{tb} \mid = 0.9986 \text{ to } 0.9993.$$

Taking the upper limit for $\mid V_{td} \mid$ one obtains a lower limit for m_t. Inserting these numbers into ΔM led to the surprise

$$m_t > 50 \, \text{GeV}.$$

By 1987 it was the general belief, that the top quark mass was much smaller than 50 GeV, but we found, that it is much larger. Meanwhile the top quark was discovered. Indeed, its mass is 174.3±5.1 GeV.

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

H. ALBRECHT, A.A. ANDAM [1], U. BINDER, P. BÖCKMANN, R. GLÄSER, G. HARDER, A. NIPPE, M. SCHÄFER, W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ, R. WURTH, A. YAGIL [2,3]
DESY, D-2000 Hamburg, Fed. Rep. Germany

J.P. DONKER, A. DRESCHER, D. KAMP, H. KOLANOSKI, U. MATTHIESEN, H. SCHECK, B. SPAAN, J. SPENGLER, D. WEGENER
Institut für Physik [4], Universität Dortmund, D-4600 Dortmund, Fed. Rep. Germany

C. EHMANN, J.C. GABRIEL, T. RUF, K.R. SCHUBERT, J. STIEWE, K. STRAHL, R. WALDI, S. WESELER
Institut für Hochenergiephysik [5], Universität Heidelberg, D-6900 Heidelberg, Fed. Rep. Germany

K.W. EDWARDS [6], W.R. FRISKEN [7], D.J. GILKINSON [8], D.M. GINGRICH [8], H. KAPITZA [6], P.C.H. KIM [8], R. KUTSCHKE [8], D.B. MACFARLANE [9], J.A. McKENNA [8], K.W. McLEAN [9], A.W. NILSSON [9], R.S. ORR [8], P. PADLEY [8], J.A. PARSONS [8], P.M. PATEL [9], J.D. PRENTICE [8], H.C.J. SEYWERD [8], J.D. SWAIN [8], G. TSIPOLITIS [9], T.-S. YOON [8], J.C. YUN [6]
Institute of Particle Physics [10], Canada

R. AMMAR, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK
University of Kansas [11], Lawrence, KS 66045, USA

B. BOŠTJANČIČ, G. KERNEL, M. PLEŠKO
Institut J. Stefan and Department of Physics [12], Univerza v Ljubljani, 61111 Ljubljana, Yugoslavia

L. JÖNSSON
Institute of Physics [13], University of Lund, S-223 62 Lund, Sweden

A. BABAEV, M. DANILOV, B. FOMINYKH, A. GOLUTVIN, I. GORELOV, V. LUBIMOV, V. MATVEEV, V. NAGOVITSIN, V. RYLTSOV, A. SEMENOV, V. SHEVCHENKO, V. SOLOSHENKO, V. TCHISTILIN, I. TICHOMIROV, Yu. ZAITSEV
Institute of Theoretical and Experimental Physics, 117 259 Moscow, USSR

R. CHILDERS, C.W. DARDEN, Y. OKU
University of South Carolina [14], Columbia, SC 29208, USA

and

H. GENNOW
University of Stockholm, S-113 46 Stockholm, Sweden

0370-2693/87/$ 03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division) 245

Figure 26: The frontpage of the ARGUS paper on the observation of $B^0\overline{B^0}$ mixing

Figure 27: The author congratulating at the 1987 ARGUS collaboration meeting held at Bled

Since our result on $B\overline{B}$ mixing was not in conflict with the Standard Model, we decided to publish [14]. The frontpage of the paper with the list of the authors is shown in Fig.26.

Due to the large mixing rate, it became clear that CP-violation is observable in B-meson decays, which represented the unique possibility to determine the imaginary part of the CKM matrix. Thus a new field of research was opened up, which was then persued by Babar at SLAC and Belle at KEK.

The observation of $B^0\overline{B^0}$ mixing would have been the most important event in particle physics in 1987, had not the universe presented an even more spectacular event, the supernova explosion SN 1987A.

10 Acknowledgements

It is a pleasure to thank the DESY directors, Profs. H. Schopper, V. Sörgel, G. Weber, E. Lohrmann, P. Söding and G. Voss, who provided us an excellent opportunity to do exiting physics. We also thank the DORIS machine group, especially Prof. K. Wille, Dr. H. Nesemann and B. Sarau, for their efficient run-

ning of the storage ring and their competent cooperation.

11 References

[1] H. Hasemann et al., DESY-Proposal No. 148 Oct. (1978)
[2] The ARGUS drift chamber, M. Danilov et al. Nucl. Instr. Meth. 217 (1983) 153.
[3] H. Nesemann et al., DESY preprint DESY M-80/89, (1980) in: Proc. Geneva Accel. Conf. (1980) 315.
[4] ARGUS: A universal detector at DORIS-II, H. Albrecht et al., Nucl. Instr. Meth. A 275 (1989) 1.
[5] The ARGUS electron-photon calorimeter
1. Detection of low energy electromagnetic showers, A. Drescher et al., Nucl. Instr. Meth. 205 (1983) 125.
2. Properties of the light collection system of the lead scintillator shower counters, A. Drescher et al., Nucl. Instr. Meth. 216 (1983) 35.
3. Electron-hadron separation, A. Drescher et al., Nucl. Instr. Meth 237 (1985) 464.
[6] The ARGUS time-of-flight system, R. Heller et al,. Nucl. Instr. Meth. A 235 (1985) 26.
[7] Muon chambers of the ARGUS detector (in Russian), A.V. Arefiev et al., Prib. Tekh. Eksp.2 (1986) 66.
[8] The ARGUS vertex drift chamber, K.W. Edwards et al., Nucl. Instr. Meth. A 252 (1986) 384.
The ARGUS microvertex detector, E. Michel et al., Nucl. Instr. Meth. A 283 (1989) 554.
[9] A. Bean et al., CLEO, Phys. Rev. Lett. 58 (1987) 183, T. Schaad et al., MARK II, Phys Lett 160B (1985) 188, W. Bartel et al., JADE, Phys. Lett. 146B (1984) 437.
[10] C. Albajar et al., UA1, Phys. Lett. 186B (1987) 247.
[11] M.K. Gaillard and B.W. Lee, Phys. Rev. 10D (1974) 897.
[12] S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D2 (1970) 1285.
[13] A. Ali and Z.Z. Aydin, Nucl. Phys. 148 (1978) 165, J.S. Hagelin, Phys. Rev. D 20 (1979) 2893; J.S. Hagelin, Nucl. Phys. B 193 (1981) 123. M.J. Vysotzki, Sov. J. Nucl. Phys. 31 (1980) 797, T. Inami and C.S. Lim, Prog. Theor. Phys. 65 (1981) 297.
[14] H. Albrecht et al., ARGUS, Phys. Lett. B 192 (1987) 245.