arXiv:2208.11076v1 [hep-ex] 23 Aug 2022

The JADE Experiment at the PETRA e^+e^- collider - history, achievements and revival

S. Bethke[1*] and A. Wagner[2*]

[1]Max-Planck-Institute of Physics, Föhringer Ring 6, Munich, 80805, Germany.
[2]DESY, Notkestr. 85, Hamburg, 22607, Germany.

*Corresponding author(s). E-mail(s): bethke@mpp.mpg.de; albrecht.wagner@desy.de;

Abstract

The JADE experiment was one of five large detector systems taking data at the electron-positron collider PETRA, from 1979 to 1986, at e^+e^- annihilation centre-of-mass energies from 12 to 46.7 GeV. The forming of the JADE collaboration, the construction of the apparatus, the most prominent physics highlights, and the post-mortem resurrection and preservation of JADE's data and software are reviewed.

Contents

1 Introduction

JADE was a particle detector system and experiment at the electron-positron collider PETRA at the DESY laboratory in Hamburg, Germany. It was designed, constructed and operated by an international collaboration of institutes from **JA**pan, **D**eutschland and **E**ngland [1]. From 1979 to 1986, the experiment recorded data of electron-positron annihilations at centre-of-mass energies between 12 and 46.7 GeV.

The detector comprised novel technologies like accurate tracking of charged particles in the central jet chamber with fast multi-hit electronics, measurement and identification of photons, electrons and muons over wide regions of solid angle, and maximal hermiticity and symmetry of the detector systems. Scientific highlight results were the (co-)discovery of the gluon, establishment of precision jet-physics, tests of Quantum-Chromodynamics, first evidence for the asymptotic freedom of quarks and gluons, establishment of string-hadronisation, electro-weak precision tests, two-photon physics and searches

for New Physics like Super-Symmetry, free quarks and the - at that time still undiscovered - top-quark.

More than 10 years after close-down of the experiment, the JADE software and data were revived and rescued to modern storage systems and computing platforms, showcasing the need for data preservation and re-use in particle physics and beyond [2]. These post-mortem efforts provided the means for a second series of PhD-theses and scientific publications, based on novel analysis methods and improved theoretical calculations and models that were not available during the life-time of the experiment.

In this article, the history and the development of the JADE experiment, the revival and preservation of its data and software, and some of its major scientific achievements are being reviewed.

2 Historical environment

About 50 years ago, particle physics was boosted by a number of ground-breaking experimental discoveries and theoretical developments. In 1973, the discovery of weak neutral currents in neutrino scattering experiments at CERN in Geneva / Switzerland provided experimental evidence [3] for the validity of the unified theory of the electro-weak interaction, the "Standard Model", that was developed since the 1960s [4, 5, 6], and was honoured by the Nobel price for Sheldon Glashow, Abdus Salam and Steven Weinberg in 1979 [7].

In November 1974, a fourth species of quarks, the charm-quark, was discovered by the E598 experiment at Brookhaven National Lab (BNL) in New York [8], and the SLAC-LBL magnetic detector at the electron-positron accelerator SPEAR at the Stanford Linear Accelerator Centre (SLAC) in California [9]. Called the "November Revolution", this discovery triggered a series of new developments in the field of particle physics, and earned the Nobel price for Burton Richter (SLAC) and Samuel Ting (MIT) in 1976 [10].

First evidence for the existence of a third, sequential lepton, the τ-lepton, was reported in 1975 [11], from data of the SLAC-LBL magnetic detector at SPEAR, for which Martin L. Perl received the Nobel Prize in 1995 [12].

The symmetry of two doublets of quarks as basic constituents of hadronic matter did not last very long: in 1977, a narrow resonance observed at Fermilab close to Chicago revealed the existence of a fifth species of quarks, called the b-, beauty- or bottom-quark [13].

The theory of the strong interaction between quarks, Quantum-Chromodynamics (QCD), started to emerge in the 1960s, and was completed in the early 1970s by introducing colour octet gluons as carriers of the strong force [14], by the concepts of asymptotic freedom [15, 16] and of confinement of quarks, at high and at low energy scales, respectively. Based on QCD, the formation of observable hadron jets as footprints of quarks and hard gluon emission was predicted and quantified [17, 18], paving the way for experimental verifications and further possible discoveries.

During this exciting time of modern particle physics many new projects for particle colliders were discussed and planned in Europe, the United States, in Japan and in Russia. At DESY, the German laboratory for particle physics at Hamburg, the e^+e^- collider DORIS had been commissioned in 1974, just after the "November Revolution", contributing with the observation of higher mass excitations of the newly discovered J/Ψ charm-quark-antiquark states.

In 1973, during a meeting of the European Committee for Future Accelerators, ECFA, about long-term plans for new accelerators in Europe it emerged that DESY, the Rutherford Appleton Laboratory (then called RHEL) in the UK, and the INFN laboratory in Frascati/Italy considered construction of a large e^+e^- storage ring. There was consensus that only one such collider should be built in Europe. In 1975 the Administrative Council of DESY concluded that the plan of an electron-positron storage ring for energies around 20 GeV was scientifically very well founded, and that DESY offered the best conditions in Europe for the realisation of such a project, since the existing experimental facilities would be fully used. DESY was asked by the German Government to continue its efforts to secure international scientific and financial support and to prepare for the international use of the project.

Intense negotiations of the DESY Director Herwig Schopper with the German government led to the approval of the Positron-Electron-Tandem-Ring-Anlage at DESY, PETRA [19], already in the fall of 1975. The foundation for experiments at the PETRA e^+e^- collider was laid at the Discussion Meeting on PETRA Experiments, held at Frascati/Italy from March 1 to 5, 1976 [20]. At this meeting, presentations about the physics goals, technical requirements and proposals for experimental setups were given and discussed, and first steps to form collaborations for experiments at PETRA were taken.

Under the leadership of Gustaf-Adolph Voss, the Director of Accelerators, who already had led the design efforts, construction of PETRA began in 1976, and was completed in 1978. First stored beams were established in July 1978, six months ahead of the initial planning. The initial experiments operating at the 4 collision regions of PETRA were the JADE [21], Mark-J [22], PLUTO [24] and TASSO [23] detectors. PLUTO had already operated [25] at the precursor storage ring DORIS, and was replaced at PETRA in March 1980 by the newly built CELLO detector [26].

The timeline of PETRA as e^+e^- storage ring and collider is summarised in Table 1.

After its shutdown as particle collider in November 1986, PETRA came back to life in 1990 as PETRA-II, where it served as pre-accelerator for the electron-proton collider HERA until 2007. From 1995 PETRA-II also operated as synchrotron radiation source, and from 2007 to 2009 was converted into a highly brillant X-ray source, PETRA-III.

With PETRA and four large experimental setups starting to operate in 1979, DESY became a nationally funded, yet internationally used research laboratory in the field of particle physics. Fig. 1 schematically shows the PETRA collider, with its 4 experimental halls and experiment sites.

**Table 1** Timeline of the e^+e^- storage ring PETRA

Date		Event
1974	September:	proposal for an e^+e^- storage ring of 2304 m circumference, with beam energies E_b up to 19 GeV and luminosity up to 1.2×10^{32} cm^{-2} s^{-1}
1975	Fall :	approval by federal government
1976	March 1-5:	discussion meeting on PETRA experiments, Frascati (Italy)
	Spring:	start of PETRA construction; formation of PETRA Research Committee (PRC); call for experimental proposals
	August:	12 experimental proposals received
	October:	5 proposals recommended for approval (CELLO, JADE, Mark-J, PLUTO, TASSO)
1977	February:	PETRA magnet series production started
1978	July:	early completion of PETRA, start of operation
	September:	first e^+e^- collisions
	October:	Mark-J, PLUTO, TASSO detectors moved into beam
1979	January:	first experimental results; JADE detector moved into beam
	April 26:	official inauguration of PETRA with presence of the President of the Federal Republic of Germany, Walter Scheel
	November:	E_b up to 19 GeV
1983		Energy upgrade: E_b up to 22 GeV
1984	March:	maximum E_b of 23.390 GeV
1986	November 3:	final shutdown of PETRA and experiments

3 The JADE detector and collaboration - planning, set-up and operation

3.1 Planning

The initial founders of the JADE collaboration were Joachim Heintze, Professor at the Physikalisches Institut of Heidelberg University, Masatoshi Koshiba, Professor at Tokyo University, and Shuji Orito, scientist at the Max-Planck-Institute for Physics at Munich and later head of the newly setup Laboratory of International Collaboration on Elementary Particle Physics (LICEPP) at Tokyo University.

At Frascati, Heintze, at that time spokesperson of the DESY-Heidelberg NaI Lead Glass detector operating at the DORIS storage ring at DESY, presented a talk on "Ideas how to use the DESY-Heidelberg Equipment at PETRA", and pointed out the importance to measure as many parameters as possible of all particles emerging from the e^+e^- annihilation processes. Orito, at that time member of the DASP experiment at DORIS, presented "A 4π Detector with good Electron and Muon Identification", and also stressed the importance of obtaining the most complete and precise information on the kinematics of PETRA collision events. Furthermore, Robin Marshall from Daresbury Lab (UK) reported ideas on "A Magnetic Detector with Lepton and Photon Identification", and Wulfrin Bartel from DESY and the University of Hamburg, like Heintze member of the DESY-Heidelberg experiment, presented plans for an "Electron-Hadron Calorimeter for PETRA".
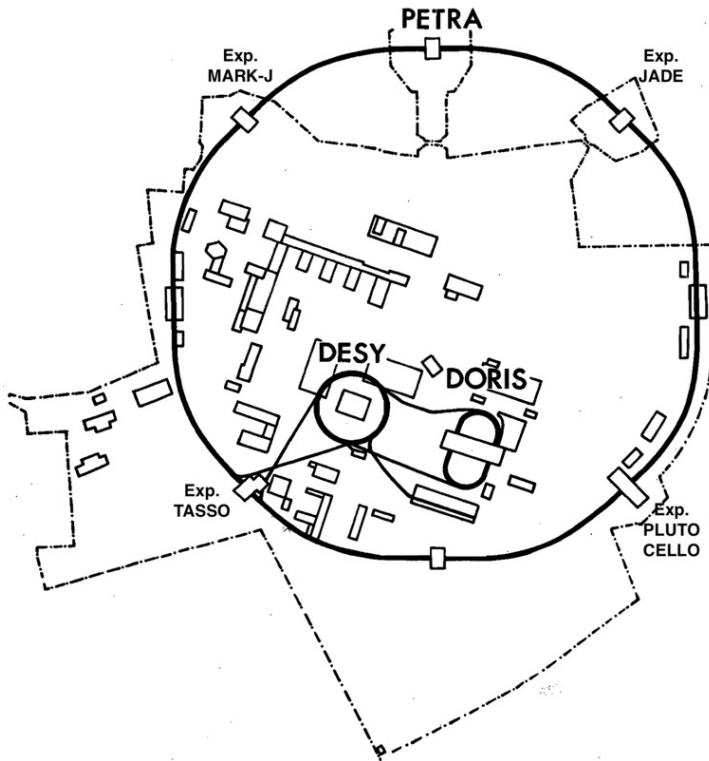
Fig. 1 PETRA and its 4 experimental halls on the DESY site (dash-dotted boundary).

As these proposals were based on the same basic principles it was natural that Heintze, Orito, Marshall, Bartel and colleagues joined forces and proposed a new magnetic detector to be operated at PETRA, with maximum sensitivity for measuring the parameters of leptons and hadrons over (close to) the full solid angle. Heintze and Orito also involved Rolf Felst, senior scientist at DESY and head of the DESY F22 group, and member of DASP as well.

The initial plan included a high resolution detector for charged particles within a magnetic coil of 30 cm radius - basically following the parameters of the DESY-Heidelberg experiment. Rolf Felst and Dieter Cords suggested a coil radius of at least 1 m. Joachim Heintze and his group, being in charge for construction of the tracking chamber, took up this proposal - which later proved to be an essential decision for the scientific success of the detector.

The groups of Heidelberg, DESY and Tokyo were joined by groups from Daresbury Lab, from University of Lancaster and from the University of Manchester, with Paul Murphy of Manchester University being the leading and most influential person of the English groups. Together, they set up the official "JADE - Proposal for a Compact Magnetic Detector at PETRA" [27], which was submitted to the DESY management by August 1976. The name of

the collaboration and experiment was derived from the country names of the founding institutes: **JA**pan - **D**eutschland - **E**ngland.

The proposal was signed by 48 authors, including 11 graduate students. The abstract provides a concise summary of the relevant key features and scientific goals of the experiment:

We propose an experiment which will be ready to take data from the first colliding beams at PETRA. The apparatus consists essentially of a system of cylindrical drift chambers placed inside a thin normal conducting solenoid. A modular array of leadglass shower counters surrounds the coil and beyond this we have a muon filter system. A small angle double tagging system is provided as a luminosity monitor and for two photon physics.

Using this apparatus we intend initially to explore the following physics:

1. *Total annihilation cross section* $e^+e^- \to$ *hadrons.*
2. *Search for new particles by detecting weak decays to* $e^\pm$ *or* $\mu^\pm$
3. *Check for QED processes at high momentum transfers and search for neutral weak current effects in* $e^+e^- \to \mu^+\mu^-$ *and* $e^+e^- \to$ *hadrons.*
4. *Study of hadronic final states.*
5. *Survey of two photon initiated reactions.*

Rolf Felst was elected as spokesperson of the JADE collaboration - a position he held until the end of the experiment in 1986. The representatives of the groups signing the proposal were Robin Marshall (UK groups), Wulfrin Bartel (DESY and Hamburg University), Joachim Heintze (Heidelberg) and Shoji Orito (Tokyo). In October 1976, the proposal was recommended for approval by the PETRA Research Council, PRC.

The participation of Daresbury Lab later changed over to the Appleton High Energy Laboratory (now Rutherford Appleton Laboratory). In spring 1984, the group around Gus Zorn from University of Maryland, USA, joined the collaboration[1].

The timeline of the JADE experiment, from its planning in early 1976 to its shutdown at the end of 1986, and its revival in the late 1990s and beyond, is summarised in Table 2.

3.2 Set-Up

Construction of the detector started right after approval of the project in October 1976. Only 2.5 years later, in January 1979, the JADE detector, fully completed, was moved into the beam in the North-West hall of PETRA . This time span seems amazingly short from today's perspective, especially as the compact detector system - about 8 m long, 6.5 m high and 7 m wide, see Fig. 2 - exhibited features and technologies that were novel and trendsetting at that time.

---

[1]At that time, the "**A**" in "JADE" was unofficially redirected to the new **A**merican group, such that each collaborating nation was still represented by one letter of the collaboration's name.

Table 2 Timeline of the JADE experiment at the e^+e^- storage ring PETRA (PRC: PETRA Research Council; FADC: Flash Analogue-to-Digital Converter).

Phase	Date		Event
planning and construction	1976	March 1-5 August October	discussion meeting on PETRA experiments, Frascati (Italy) JADE proposal submitted to DESY management JADE proposal recommended for approval by PRC
installation and start-up	1979	February March March 26 April 1 June July 31 August 23	JADE detector moved into beam first data recorded (single e^--beam, $E_{beam} = 11.3$ GeV) fatal beam loss and damage of tracking chamber removal of detector from the beam and tracker repair reinstallation and data taking very first results presented to PRC by J. Heintze first results and evidence for the observation of the gluon presented at 9th Int. Symp. on Lepton/Photon Interactions at High Energies, Batavia, by S. Orito
upgrades	1981 1982 1984 1985		mini-beta quadrupoles and reconfigured forward detectors new lead-glass counters in central barrel installation of vertex chamber and z-chamber FADC upgrade of jetchamber read-out
shutdown	1986 1991	Nov. 3	shutdown of PETRA and the JADE experiment phasing-out of JADE data analyses
data preservation and revival	1996 1997 1997 2009 2011 2022	- 2012 August 22	data sets rescued and copied to modern data carriers revival of JADE software new data analyses and scientific publications JADE revival and collaboration meeting digitisation and archiving of shift crew logbooks (1979 -1986), collaboration meeting protocols and internal notes release of JADE data and software for public access and usage, in the framework of the CERN Open Data portal.

3.2.1 The JADE Detector

The detector covered 97 % and 90 % of the full solid angle for detecting charged particles and photons, respectively [21]. A 3.5 m long solenoidal coil, 2 m in diameter and with a 7 cm thin aluminum conductor, produced a magnetic field of 0.5 Tesla parallel to the electron/positron beam axis. An array of 24 scintillators surrounded the beam pipe, and 42 time-of-flight-counters were mounted immediately inside the coil.

A cylindrical, novel type of drift chamber, the "jet chamber" [28], was located inside the magnet volume, to accurately measure the tracks of charged particles that emerge from the e^+e^- interaction point in the beam pipe and centre of the detector. A cylindrical array of lead-glass shower counters was arranged outside of the magnet coil, consisting of 2520 lead glass blocks, individually calibrated, reaching an energy resolution for large angle Bhabha events ($e^+e^- \to e^+e^-$) of $\sigma_E/E = 4\%/\sqrt{E} + 1.5\%$.

Two flat iron endcaps with 96 lead glass blocks on each inner side served as part of the magnet return yoke, closed the cylinder and completed the lead glass system to a total coverage of 90% of the solid angle. The magnet return
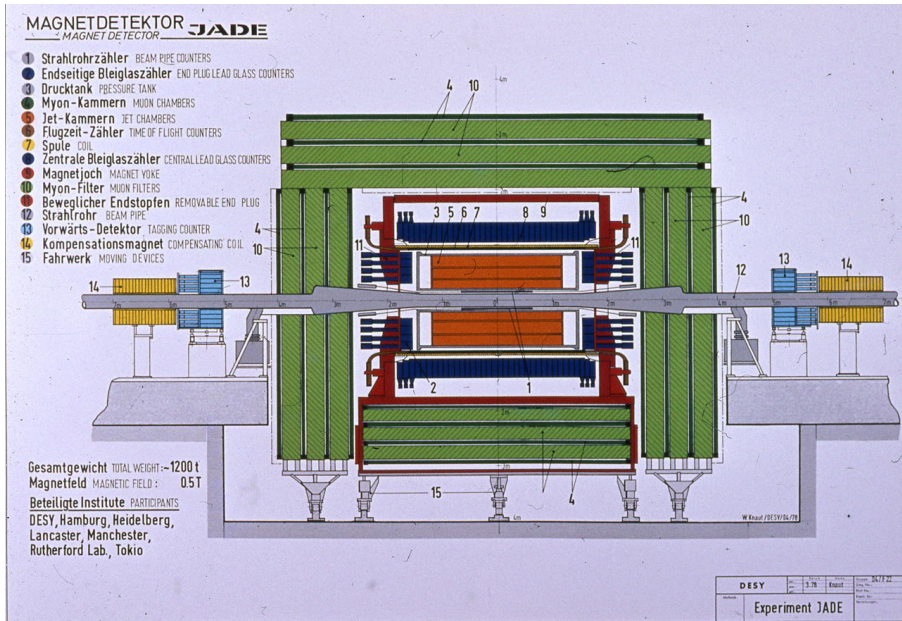
Fig. 2 The JADE detector in its 1979 configuration.

yoke surrounded the lead glass system and also served as the first layer of the muon filter, followed by further layers consisting of iron loaded concrete, interspersed by 4 or 5 layers of drift chambers covering 92% of the solid angle.

Two small detectors, consisting of scintillators, drift chambers and lead-glass modules, recorded electrons and positrons at small polar angles (measured with respect to the direction of the incoming positron beam), providing online measurement of the luminosity of the colliding beams, and tagging two-photon processes ($e^+e^- \rightarrow e^+e^- +$ hadrons). For a concise description of all components of the JADE detector, see also [29].

The jet chamber, together with the lead-glass calorimeter, was the key component enabling JADE's scientific success. Developed, constructed and commissioned by the Heidelberg group around Heintze, it consisted of 96 drift cells, arranged in 3 concentric rings around and parallel to the beampipe, each containing 16 sense wires and 19 potential wires plus a system of field generating electrodes defining linear drift spaces up to 8 cm long, see Fig. 3. The chambers were contained in a pressure vessel, 3m long and 1.8m in diameter, filled with a gas mixture of Argon, Methane and Isobutane at 4 atm.

Charged particles, emerging from the beam collision point and traversing the jet chamber, ionise the gas along their curved[2] trajectory, leading to a 3-dimensional measurement of up to 48 space-points for each track. The z-coordinate along the beam direction was determined by charge division, the ratio of signal amplitudes read-out on both ends of the sense wire; the
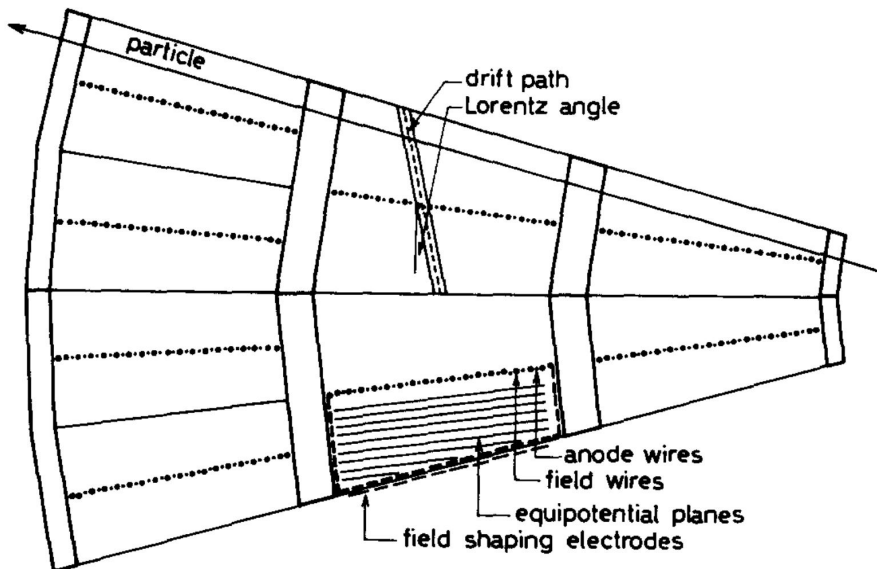
---

[2]through the magnetic field

Fig. 3 Cross section through two of the 24 sectors of the jet-chamber.

radial distance r to the beam line was given by the location of the sense wire, corrected for effects of the Lorentz force on the drifting electrons; the azimuthal position ϕ in the plane perpendicular to the beamline was given by the drift-time and hence the distance to the sense wire, whereby the left-right ambiguity was resolved by alternating displacements of the wire positions by $\pm 150 \mu$m. The spacial resolutions obtained were $\sigma_{r\phi} = 180 \mu$m (110μm after the electronics upgrade to Flash ADCs, see Section 3.3.3) and $\sigma_z = 16 - 32$ mm.

The electronics for readout and digitisation of data from the jet chamber also was custom-made, developed and built by the Heidelberg group [30], comprising pre-amplifiers at both ends of each sense wire, sitting on the outer side of the end flanges of the pressure vessel, NIM-type[3] amplifier/discriminator/integrators generating pulse height "right", pulse height "left" and time signals for each sense wire, followed by CAMAC-type[4] time and amplitude digitisers with multiple hit capacity, see Fig. 4. The system was able to process up to 8 hits per signal wire with a double pulse resolution down to 70 ns, corresponding to 3.5 mm in space at a drift velocity of 5 cm/μs. The charge measurement was performed using gated integrators, fast analog memories and a 12-bit multiplexer-ADC system (one per 8 wires). With this system, three-dimensional track coordinates and the energy loss of the particles passing the detector could be obtained.

---

[3]Nuclear Instrumentation Module (NIM) standard, defining mechanical and electrical specifications for electronics modules used in experimental particle and nuclear physics[31].

[4]Computer-Aided Measurement And Control (CAMAC), a modular crate electronics and bus standard for data acquisition and control [31].
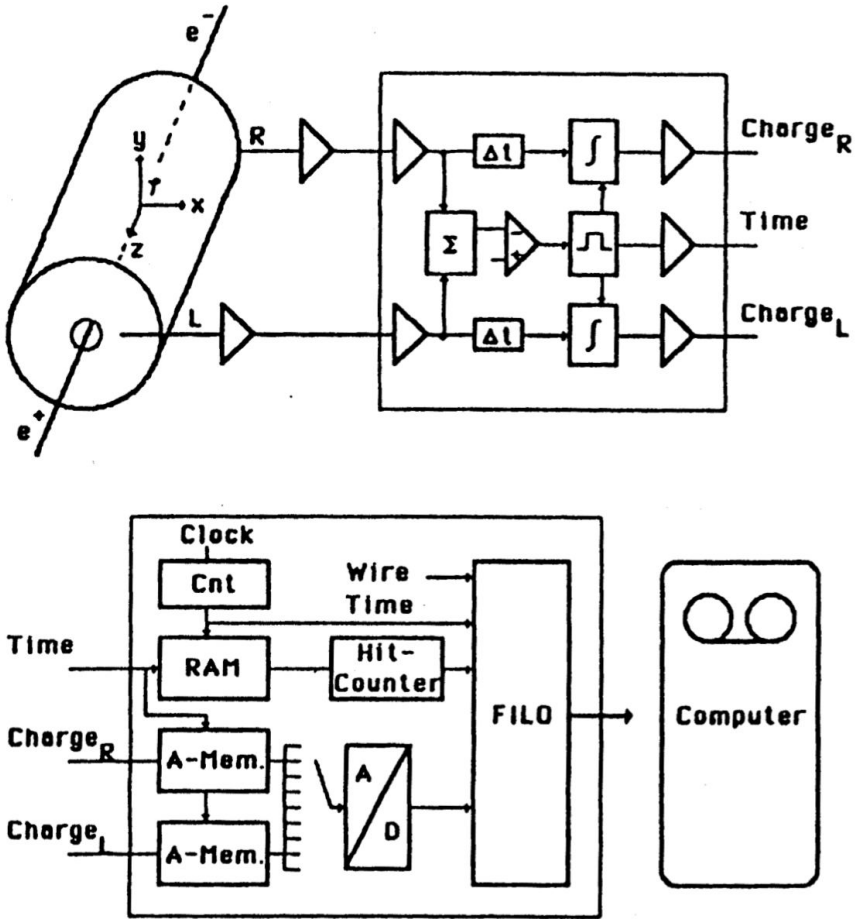
Fig. 4 Multihit electronics of the JADE jet chamber with analog pulse discrimination and charge integration.

Both the concept and realisation of the jet chamber and its associated multi-hit readout electronics were novel developments at that time, generating high expectations for its capabilities and performance. While this concept raised critical scepticism in the early phase of planning and approval, it contributed in a major way to the scientific success of JADE.

3.2.2 Event Selection and Data Acquisition

The two electron- and two counter-rotating positron-bunches crossed each other, at each of the four interaction points of PETRA, every 4 μs, i.e. at a rate of 250 kHz. The JADE trigger system reduced this rate to a few collision events per second which were read out and stored for physics analyses.

The trigger was organised in three levels, T1 to T3. The first level (T1) was based on fast analog signals from the scintillators and the lead glass counters,
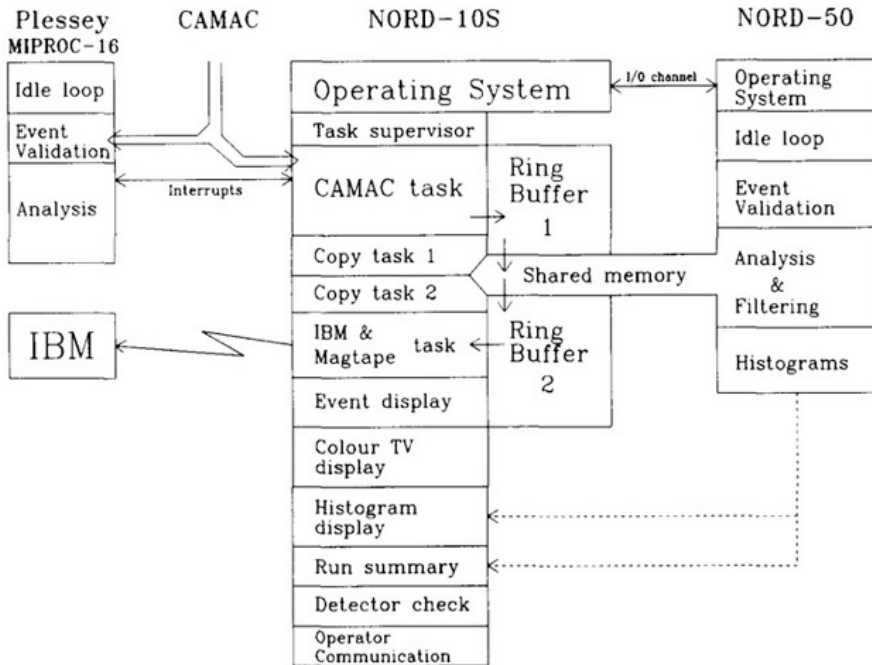
Fig. 5 The JADE data acqusition system (JDAS) [32].

which were available about 350 ns after the beam crossing. Based on certain requirements of configurations or energy sums, collision events were immediately rejected, or postponed to the next level (T2), or immediately accepted for read-out. Rejection at this stage allowed to reset the trigger and read-out system, without causing dead-time.

The level 2 trigger was based on the data of the tracking chamber and a fast track-finding logic, which were available about 2 μs after beam-crossing. Until 1982, rejection by T2 caused the loss of the next bunch crossing because of the time needed to reset the jet chamber electronics. From 1982, this was changed such that a T2-reject did not generate extra dead-time.

Finally, trigger level 3 used signals from the muon counters which were available about 5 μs after beam-crossing. Events accepted at any stage of T1 to T3 initiated an interrupt signal to the online computers which read out the digitised event information.

The average amount of data read out for a typical e^+e^- collision event was 200 to 3500 16-bit words, ocuring at a trigger rate between 2 and 6 Hz, depending on the PETRA beam conditions. Multihadronic events, at a rate of a few per hour, typically comprised 4000 to 8000 words. In the initial phase of the experiment, the data were written on magnetic tapes, which were then carried over to the DESY main frame computer centre for further processing and data analysis. Later, data were directly transferred to the computing centre using a link between the JADE online computer and DESY's IBM main frame.

Efficient operation and control of a complex detector like JADE required a maximum of on-line computing power, memory and data handling capacity. At the time of JADE operation, computing power as well as memory capacity was very limited, many orders of magnitude less than available today. The choice made for the JADE experiment was a NORD-10s/50 dual processor from Norsk-Data, Norway, and a Plessey MIPROC-16 microprocessor.

The NORD-10s was a general purpose 16-bit minicomputer for time-sharing applications and real-time multiprogram systems. The CPU consisted of a total of 24 printed circuit boards, and its speed was 260 ns per micro-instruction [33], corresponding to a CPU clock speed of 3.8 MHz. The memory management system allowed a 16-bit virtual word address to be mapped into an 18-bit physical address, so that the maximum memory available to a user program was 128 kbytes and the maximum physical memory was 512 kbytes. In addition the memory management system swapped 2 kbyte pages to and from a 66 Mbyte disc, thereby extending the memory size "almost indefinitely" [34].

The NORD-10s was equipped with two 66 Mbyte disc units, two floppy-disc units, one card reader, a 1600 b.p.i. magnetic tape unit, ten terminal drivers and two external bus drivers (one for CAMAC I/O and the other for a crate that provided the link to the DESY IBM mainframe computer), a colour TV screen and a Gould black-and-white printer/plotter.

The NORD-50 was a 32-bit single-program computer which was about a factor of 3 faster than the NORD-10. It controlled no peripherals at all and needed a NORD-10 which drove it via a set of registers. The particular advantage of the NORD-10s/50 system was that the two processors could access a common part of a multiport memory and were not simply linked by I/O channels.

For digitising the data and controlling the electronics for the JADE experiment, 40 CAMAC crates were interfaced to the NORD-10s. The MIPROC-16 was used for part of the online event filtering scheme. The NORD-50 was used for a single program which performed event validation, analysis and monitoring, including histogram filling [32]. Several microprocessors operated within individual crates and for various purposes. The organisation of the tasks and buffers of the JADE Data Acqusition System (JDAS) is shown in Fig. 5.

3.2.3 Offline Computing, Data Analysis and Monte Carlo generation in a time before internet

At the end of the 1970s, the central computer at DESY was based on a system of two IBM 370-168 mainframes that were installed in 1975, each with a main core memory of 3 MByte[5]. The system was upgraded in 1979 by the purchase of an additional mainframe IBM 370-3033, which basically doubled the total

---

[5]The main memory was already based on silicon technology, in contrast to magnetic-core memory that was the predominant form of random-access computer memory before 1975. 1975 also marked the transition from punch-card programming to a terminal based time-sharing system (TSO). This transition happened slowly and was completed at DESY by 1979.

available CPU power. The 3033 provided a cycle time of 58 ns, equivalent to a CPU clock speed of 17.2 MHz.

During data taking, the JADE raw data were transferred to the DESY computing centre using a fast internal link, and written on machine-room tapes with a capacity of 160 MB each ("REFORM" data sets). These data were then further processed, calibrated, reduced, and pre-analysed off-line on the IBM mainframe, and the resulting data files, called "REDUCn", with n=1 being the main stream for all selected data, and n=2 for a special selection with slightly varied selection criteria better adopted to the needs of two-photon physics, were again written to machine room tapes.

Due to the absence of the internet or any of its precursors, the data basically resided at DESY, and physics analyses proceeded mainly on the DESY IBM mainframe. Also the generation of Monte-Carlo based event samples, required for the study and correction for limited detector response and resolution, was performed on the DESY IBM mainframe. As all the PETRA experiments processed their data in a similar way, the DESY computing system was almost always operated and used at its limits, and there was need for significantly more computing resources than available at DESY, e.g. for reprocessing of all data sets, or for sufficiently large statistics and variants of MC production. This was a major bottleneck requiring innovative, farsighted and collegial usage of the available computing resources.

There were, however, occasions of accessing and using significant additional off-line computing resources for JADE. The Tokyo group of JADE faced the problem that many of their students needed to perform and finalise their data analyses back at Tokyo, due to limited resources for student's travels and staying abroad. The group therefore acquired and installed a FACOM M190 mainframe system, a clone of and thus compatible to the IBM 370, at their lab at Tokyo. That computer was equipped with a copy of the DESY software system, such that the JADE software and all computing jobs at this machine ran exactly like at DESY, without further modifications and adjustments. Being well-equipped with local computing power, this also allowed for additional reprocessing runs of the data, and for extensive MC event generation. The in- and output-data, however, always had to be transferred by sending large batches of magnetic tapes (c.f. Fig. 22), between Tokyo and DESY.

Another occasion for using significant extra off-line computing resources was procured by the Heidelberg group: The mainframe computer of the University of Heidelberg, an IBM 3081 - a successor of the IBM 370 series - at that time was routinely switched off during week-ends, due to low user demands and also for saving resources. In 1983, the JADE group at Heidelberg succeeded to obtain permission for exclusive usage of the entire computing centre over week-ends, free of charge, but supplying its own team of trained (student)

operators for that time, for mounting in- and output tapes but also for assuring smooth operation of the hard- and software systems, and for switching on and off the computer centre for these special weekend operations[6].

3.3 Operation and Detector Upgrades

In spite of the very short time for planning, construction and commissioning, the detector performed as expected right after its completion and installation in February 1979.

3.3.1 Early Set-Backs

However, already on March 26 1979, a fatal loss of the PETRA beam right into the detector resulted in major damage of the jet chamber, c.f. Table 2. The beam loss was caused by a trip of part the magnet system due to a failure of the cooling water supply. The electrons of the PETRA beam hit the beampipe close to the JADE detector, producing showers of energetic particles traversing the jet chamber, ionising the gas and causing major distortions of the electric field in the drift chamber. This in turn lead to large oscillations of the anode signal wires, some of which would contact the neighbouring cathode wires. Due to a too large capacity of the decoupling capacitors in the high-voltage supply for the electric fields inside the chamber, some of the 50 μm thin sense wires therefore melted when making contact with the cathode wires.

The scientists on duty at this night shift of March 26 analysed the situation and found that in more than half of the jet chamber cells at least one wire was broken and that these cells could no longer be operated.[7]

Rapid decisions and actions were taken in order to repair the damaged jet chamber. On April 1st 1979, within 24 hours the JADE detector was rolled out of the beam and the beam vacuum was reestablished. The pressure vessel with the jet chamber was removed from the surrounding detector, carefully packed into a large truck and driven back to the Physics Institute of University of Heidelberg, where the jet chamber had been built and completed just few months before. Disassembly of the chamber, its repair, re-assembly, transport back to DESY, re-installion and commissioning at DESY took little more than 2 months, such that the JADE detector started to take collision data again in June 1979.

JADE had to catch up with its competitor experiments at PETRA, MARK-J, TASSO and PLUTO, who took their first data during JADE's repair

---

[6]The installation of the JADE (and DESY) software, however, was difficult, due to a different system software on the 3081, and finally was not successfully completed. Instead, load-modules of programs being produced on the DESY mainframe proofed to run without problems on the 3081, such that productions and generations that did not need much user intervention and adjustments could formidably run on the 3081. Monitoring and steering of this production at Heidelberg was performed using an early version IBM-PC at DESY, with an acoustic-coupled phone connection to the Heidelberg mainframe with 800 baud transfer speed. However, the transfer of in- and output data, and of the load modules, had to be arranged via large magnetic tapes, being transported by scientists travelling between Hamburg and Heidelberg by train.

[7]They must have been shocked as the only thing they noted in the experiment's log book was: *6:40 Strahl verloren (beam lost) END.*

shutdown. The very first results obtained in this previously unexplored energy range showed that the total hadronic cross section, a measure for the number of quark generations, showed no evidence for the hypothetical top-quark. However, these early data already exhibited first signs for *the* major discovery to be made at PETRA, the gluon - see Section 4 below.

Data taking of JADE started right after re-installation and commissioning of the detector, and very first analysis results of these early JADE data were already presented at the PRC[8] meeting on July 31 1979 by Joachim Heintze, and at the 9th International Symposium on Lepton-Photon Interactions at High Energies, held at Fermilab / Batavia (USA) in August 23-28, 1979, in a talk given by Shuji Orito [36].

In the course of 1980 running, a total of 9 out of the 96 drift cells of the central jet chamber developed HV-shortages, so that these had to be taken out of HV-supply and data-readout ("dead cells"). As a consequence, the detector was again opened and the jet chamber vessel removed and driven to Heidelberg for repair, in the winter shutdown of PETRA of 1980/1981. The repair work was completed during the scheduled shutdown.[9]

3.3.2 Routine Running

The JADE detector recorded e^+e^- collision data from June 1979 to November 1986, when PETRA was finally shut down. The variation of the centre-of-mass energy $\sqrt{s}$ as a function of time is summarised in Fig. 6, and the integrated luminosity recorded at the different energies is given in Fig. 7. The total integrated luminosity summed up to 216 pb^{-1}.

In the first three years of running, PETRA and the experiments operated in 24/7 mode for typically few weeks in a row, intercepted by short periods of shut-down for maintenance and upgrades of the accelerator and the detectors. During the last years of operation, extended data runs lasting several months became common routine.

Detector operation during data-taking required two persons being on shift in the JADE control room, controlling and steering the performance of detector hardware, data taking and data flow, performing small repairs and fixes, informing and calling experts in case of major problems and happenings, and coordinating with the other experiments and the PETRA control room (PKR),

Shifts were arranged in three 8-hours shifts throughout the day, from 0:00 to 8:00, from 8:00 to 16:00 and from 16:00 o'clock to midnight. In addition, one expert for each of the major detector subsystems was assigned to be on-call for cases of major problems, typically for periods of 24 hours, adding up to a total of 12-15 people being in charge and responsible for operation of JADE every day. During times of data taking, these were major challenges for

---

[8]PETRA Research Committee; later generalised to Physics Research Committee

[9]The action was risky due to deep-winter conditions on the way to and from Heidelberg, two 600 km drives through deep snow and the need to keep the detector at temperatures safely above 15C at all times. In addition, it was a challenge to manage disassembly, repair, assembly and commissioning during the short available time over the holidays. Being experienced with this kind of emergency actions, the Heidelberg crew succeeded to deliver and re-install a fully functional jet chamber in time again.
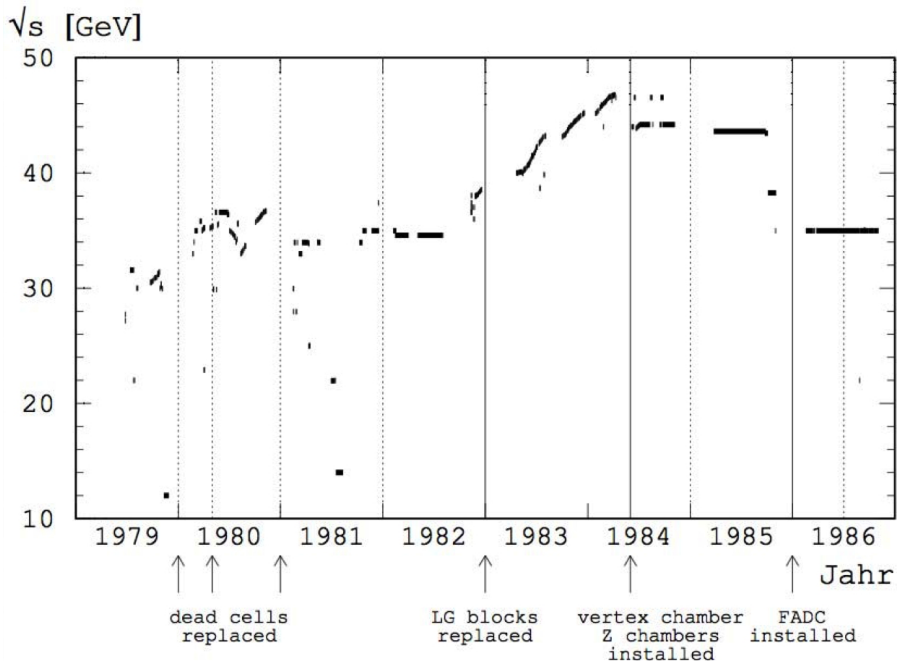
Fig. 6 e^+e^- centre of mass energies of data taken as function of time. Major repairs and upgrades of the JADE detector are indicated.

a collaboration consisting, at any given time between 1979 and 1986, of 50 to 60 people, who partly were based at their home institutions rather than at DESY.

The first data collected at run start in 1979 were at c.m. energies around 30 GeV and concentrated around 35 GeV in the course of the end of 1979 to late 1982, with short interceptions at 22 and at 14 GeV in 1981.

From late 1982 to the middle of 1984, the c.m. energy of PETRA was gradually increased, in steps of 30 MeV, from 35 GeV up to PETRA's maximum achieved energy of 46.78 GeV. At each energy point, about 200nb^{-1} were accumulated, on average, for each of the four experiments. This was the exciting time of scanning for the top-quark, the predicted but yet undiscovered 6th quark, whose mass was expected, at that time, to be about 20 GeV, and the $t\bar{t}$-ground state to have a mass between 36.8 and 38 GeV, see e.g. [37].[10]

A just-for-fun plot of the normalised total hadronic cross section, produced on-line on 21 December 1982, at the end of the 1982 energy scan, stopping

---

[10]In order to demonstrate the high levels of expectation and of motivation at that time, we reproduce some of the comments made and documented in minutes of the weekly JADE meetings, and in the online logbooks (scanned versions available at [38]):
JADE wants to find top (be-)for Xmas! (minutes of JADE meeting on 18 November 1982)
Main worry is now that we are running already above $t\bar{t}$ ground state, since Harald Fritzsch predicts $M_{t\bar{t}}^{1s} = 36,9 \pm 0.1$ GeV. The top scan reached 38.4 GeV - Oh boy! (minutes of JADE meeting on 16 December1982)
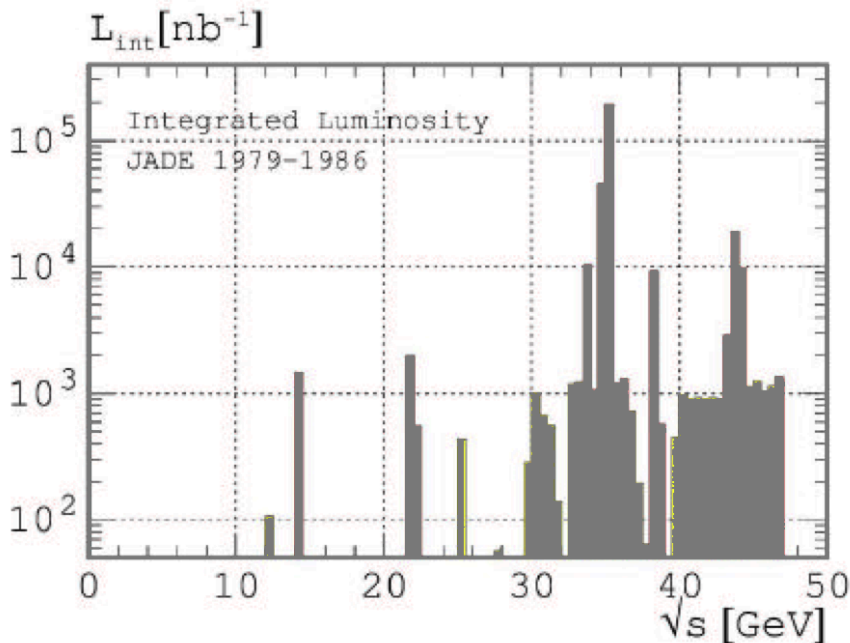
Fig. 7 Integrated luminosity collected by JADE as a function of the centre of mass energy.

at 39,5 GeV c.m. energy, including hand-drawn expectations for the lowest $t\bar{t}$ bound states according to [37], is reproduced in Fig. 8.[11]

After the disillusion of not finding the top-quark by the middle of 1984, the PETRA experiments and the PRC decided to run at c.m. energies around 44 GeV for the rest of 1984 and the entire 1985, avoiding the large drop of machine luminosity at the highest achievable energies reached during the scan. In order to significantly test QCD and its running coupling strength, JADE proposed to also collect high statistics at lower c.m. energies like 22 GeV, where only a limited amount of data had been collected in 1981. Instead, the decision was to operate PETRA at 35 GeV during its final year of 1986, to make use of the best performance and highest luminosity, thus collecting a maximum of data.

PETRA and the experiments were shut down in the early morning hours of November 3, 1986, after 8 years of successful operation. This gave rise to the earliest JADE collaboration meeting ever, starting at 6 o'clock in the morning, at the detector in the PETRA North-West experimental hall, with more than 40 Jadites present, see Fig. 9, and a formidable breakfast including a French Champagne endowed and served by Joachim Heintze.

---

[11] *Hurrah - das top ist daaaa! Und morgen kommt der Minister* (engl.: Hurrah - the top (quark) is here! And tomorrow the minister will come) was another outbreak of excitement, in April 1984, noted in the online logbook, based on a (statistically not really significant) fluctuation of R observed at the highest PETRA energy of 46,78 GeV.
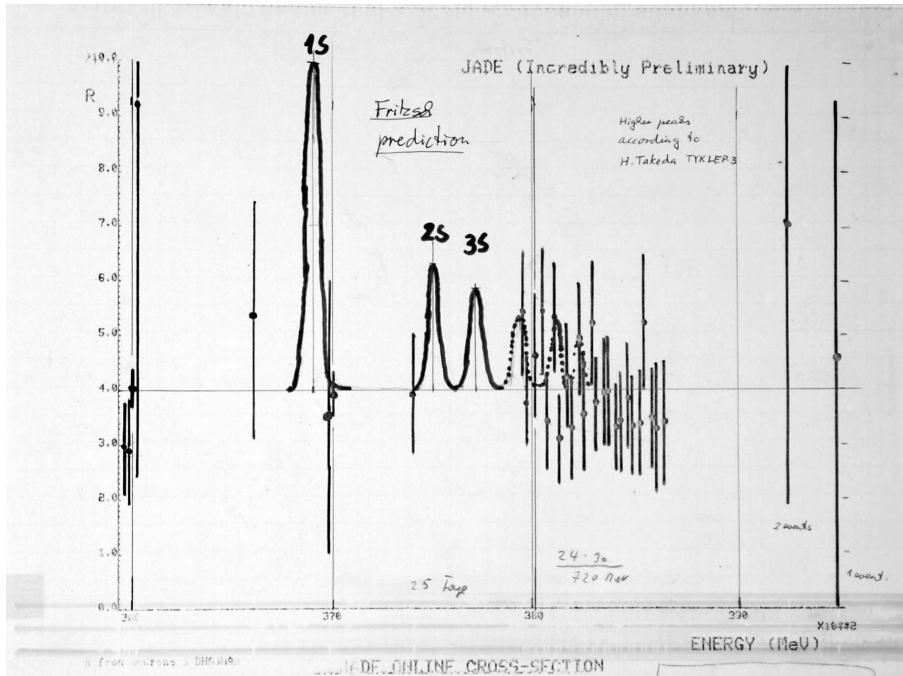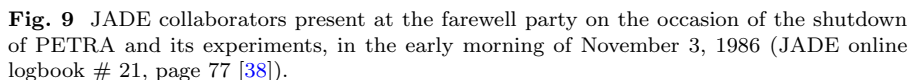
Fig. 8 Online version of the "R-plot", the normalised hadronic cross section as function of the c.m. energy, from 36 to 39.5 GeV, as plotted on 21 December, at the end of the 1982 energy scan to search for the top quark (JADE online logbook #10, page 73 [38]). Drawn-in by hand is a sketch of the expectation for the ground state and higher $t\bar{t}$ resonances according to a then actual theoretical prediction. The expectation for R in case of 5 quark flavors, without the top-quark, is 3.8, and for 6 quarks, including the top-quark in the continuum, about 5.2. The horizontal line at $R = 4$ is drawn to guide the eye.

3.3.3 Detector Upgrades

During its eight years of active lifetime, the JADE detector was subject to several major repairs, and also to a number of significant upgrades of the detector hardware. Major disassemblies of the detector and repairs of the central jet chamber during the first two years of running were already reported in Section 3.3.1. From 1981 on, the detector - in its configuration as described in Section 3.2.1 - received several major upgrades, to improve the detector performance and modernise some technologies.

- In March 1981, the beam focussing of PETRA was reconfigured to the new, so-called mini-beta scheme, which required the installation of new focussing quadrupoles on both sides of and as close as possible to the beam interaction region, for all experiments. In the case of JADE, these quadrupoles replaced the previous compensation magnets and the forward-detectors, c.f. items 13 and 14 in Figure 2. With the new scheme, no compensation magnets to counter balance the effects of the JADE solenoidal magnetic field on the beam dynamics were necessary any more; however new forward detectors

Fig. 9 JADE collaborators present at the farewell party on the occasion of the shutdown of PETRA and its experiments, in the early morning of November 3, 1986 (JADE online logbook # 21, page 77 [38]).

and a new layout of the beam-pipe had to be designed and installed inside the JADE detector. The stronger focussing of the mini-beta-scheme resulted in an increase of the luminosity, i.e. the number of collision events per second, by up to a factor of three, and thus was instrumental for the overall scientific success of the PETRA experiments.

- In the winter shutdown of 1982/83, the central 20% of lead-glass counters in the barrel region of the electromagnetic calorimeter were replaced by counters of higher density (Schott SF6), exhibiting 15.7 radiation lengths instead of the 12.5 radiation lengths of the other (Schott SF5) barrel counters.
- In 1984, a high resolution vertex chamber with Flash-ADC (FADC) readout was installed, replacing the beam pipe scintillation counters and extending the measurement of charged particle trajectories by the central jet chamber to smaller radii [39]. This upgrade of the tracking system improved the accuracy of the track extrapolation to the main interaction point by more than a factor of 2, and made precise measurements of the lifetimes of b-quarks and τ-leptons possible.
- Also in 1984, a new z-chamber was installed. It was mounted onto the outer shell of the jet chamber pressure vessel, with sense wires "wrapped" around the central tracking detector, and their sensitive drift direction parallel to the e^+e^- beam, providing a precise determination of the z-coordinate of

tracks at large distance from the beam. The installation of the z-chamber required a major operation to remove the jet chamber pressure vessel and to cut it from its high-pressure gas supply.

- Finally, during the winter shutdown of 1985/86, only one year before the end of PETRA e^+e^- collider operation, the initial multi-hit readout of the jet chamber was replaced by a 100 MHz Flash-ADC system with microprocessor pulse analysis and readout [40, 41]. This new system improved the spatial resolution of the central jet chamber from 170 to 110 μm, and the double track resolution from 7 to 2 mm. This system provided the test-bed for the tracking chamber readout at the next generation of e^+e^- experiments, in particular the OPAL detector at the LEP collider at CERN which in many respects can be considered a successor of JADE.

4 Physics Highlights

The analysis of JADE data and publication of scientific results proceeded in two phases. The first lasted from 1979 to 1991 and so came to an end about 5 years after the end of data taking. The second phase started in 1997 with the revival of the JADE data, followed by more analyses, as described in Section 5. Studies of the first phase covered a broad range of particle physics topics, predominantly in the fields of Strong Interactions and hadron production, of the Electro-Weak Standard Model, of two photon interactions, of searches for the top-quark as well as searches for new physics beyond the Standard Model. In total, 74 publications were issued in peer-reviewed scientific journals.

To date - more than 35 years after the end of data taking - these publications received more than 6800 citations, i.e. 92 citations per publication on average, and an h-index of 44 [42]. Two of these [43, 44], with 970 and 653 citations, respectively, occupy positions number one and four of the most cited papers of all PETRA experiments. Both these JADE papers pioneered jet physics and the experimental verification of Asymptotic Freedom of quarks and gluons, a key-feature of Quantum Chromodynamics.

The first publications on the discovery of the gluon, by the TASSO [45] and the Mark-J [46] collaborations, score second and third on the list of most cited PETRA publications, followed by the ones from PLUTO [47] and from JADE [48] on positions 6 and 7, respectively.

In the following subsections, some of the physics highlights of JADE will be reviewed in more detail. Only those publications will be described which received more than 100 citations; these are 14 publications out of the total of 74 by the time of writing this article. The publications not explicitly mentioned here, however, also presented significant and often pioneering results that advanced and shaped the field - see [29] for a more complete review of the physics results of JADE.

4.1 QCD and Jets

The theory of the Strong Interaction between quarks and gluons, Quantum Chromodynamics (QCD) [14, 15, 16], was formulated just a few years before the proposals for the PETRA e^+e^- collider and its experiments in 1974 to 1976, c.f. Section 3. The most outstanding results of PETRA, the proof of the existence of the gluon as carrier and exchange quantum of the Strong Force, and the verification of the force's distinct feature of Asymptotic Freedom, were not yet identified as central themes in any of the proposals of PETRA and its experiments. The general importance of hadronic final states of high energetic e^+e^- annihilations, however, was recognised as one of the central physics themes at PETRA, and has largely influenced the design and layout of the detectors - for example JADE's central tracking chamber, the jet-chamber, and its sophisticated multi-track resolution capabilities.

4.1.1 The Gluon

Topological distributions of hadrons produced in the reaction $e^+e^- \rightarrow$ hadrons revealed a predominant 2-jet like structure already at PETRA's precursor e^+e^- colliders SPEAR [49] and DORIS [50], providing evidence for the underlying process of $e^+e^- \rightarrow q\bar{q}$ and susbsequent fragmentation of the quarks to hadrons, with limited transverse momenta of the hadrons w.r.t. the initial quark directions.

In 1976, the possibility of observing a third jet at higher c.m. energies, originating from a hard gluon radiated off one of the quarks, $e^+e^- \rightarrow q\bar{q}g$, was predicted [17]. Gluon radiation in the context of QCD should lead - in increasing order of the gluon's hardness[12] - to the widening of one of the quark-jets, to a planar event configuration and, finally, to the emergence of a third jet.

Indeed, such event configurations became visible right from the start of data taking at PETRA, at c.m. energies around 30 GeV. Corresponding results were presented, first by the TASSO and then by the MARK-J, PLUTO and JADE experiments, at the European Physical Society (EPS) conference in Geneva and the Lepton-Photon Symposium at Batavia in summer 1979 [51]. The gluon discovery publications of TASSO, MARK-J, PLUTO and JADE were submitted to journals in summer 1979 [45, 46, 47, 48].

In [48], JADE reports about an excess of planar events in their sample of 287 hadronic events, at a rate which cannot be explained by statistical fluctuations in the standard two-jet process. The planar events, mostly consisting of a slim jet on one side and a broader jet on the other, are shown to possess three-jet structure by demonstrating that the broader jet itself consists of two collinear jets in its own rest system. Topological event shape distributions are compared with the predictions of model calculations based on $q\bar{q}$ production and hadronisation with different transverse momentum parameters σ_q,

---

[12] "Hard" in this context means high gluon energy and large radiation angle w.r.t. the emitting quark.
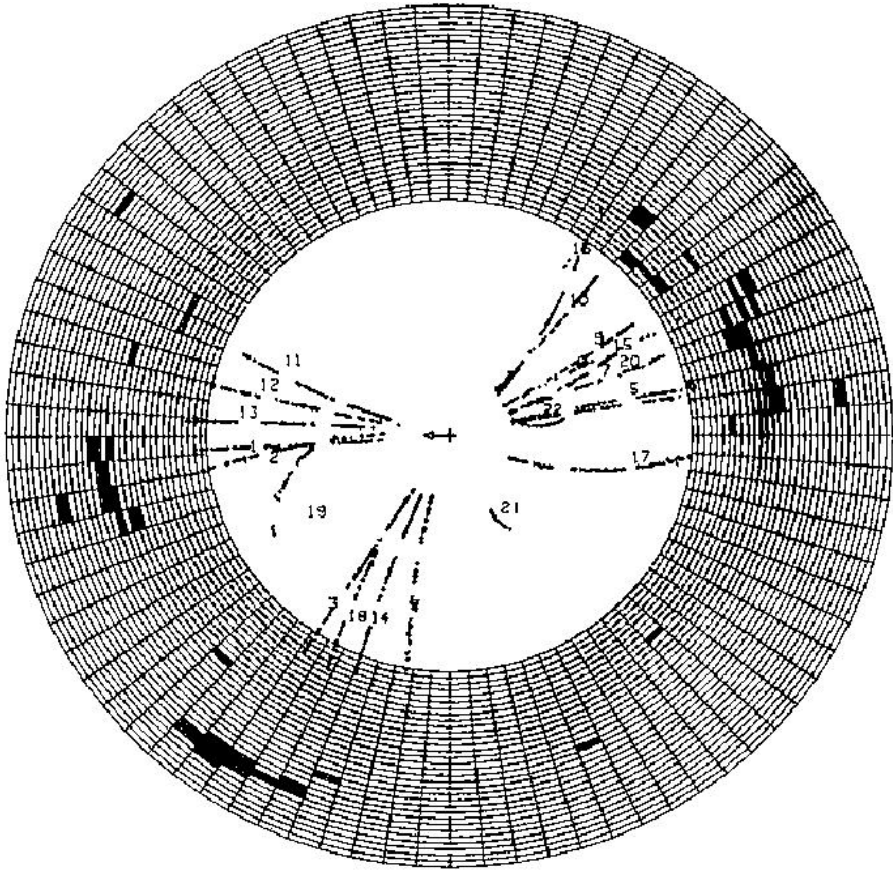
Fig. 10 3-jet event recorded at $E_{cm} = 33$ GeV, displayed as projection of hits in the central Jet-chamber to the plane perpendicular to the beam axis (central cross), and in a perspective view of the lead-glass counters. Those counters hit by particles are filled in black.

and with a model including gluon radiation to $q\bar{q}g$ final states, according to the expectations of QCD in leading order perturbation theory. These studies strongly suggest gluon bremsstrahlung as the origin of the planar three-jet events. A first estimate of the value of the strong coupling constant resulted in $\alpha_s(q = 30\ GeV) = 0.17 \pm 0.04$.

The rate of radiative gluon emission is proportional to the strength of the strong coupling constant which itself is energy dependent. At PETRA energies the fraction of events with gluon emission is around 10%. The initial evidence for 3-jet production was therefore mainly based on statistical distributions of topological event shape distributions, and comparisons with predictions of various model calculations. Nevertheless, a small number of individual hadronic events with visible 3-jet structure were already shown at the conferences in summer 1979. With more statistics gathered, the significance for gluons as the origin of planar events with clear 3-jet structures grew. A particluar nice,

"golden" 3-jet event recorded by JADE in 1981 is displayed in Fig. 10. Three well separated bundles (jets) of tracks of charged particles are clearly visible by eye, directly from the coordinates of measured hits in the jet chamber, without the need for displaying fitted track lines. The same structure is also visible from the clusters of hits in the lead-glass electromagnetic calorimeter.

4.1.2 Jet Physics

The dominant 2-jet structure and the observation of planar 3-jet events in hadronic final states at PETRA energies boosted the acceptance of the quark-parton model and of QCD as the theory of the Strong Interaction. JADE - with its high resolution central jet-chamber and lead-glass calorimeter - was well suited to develop and advance the physics of and with hadron jets, and to further use jets for significant tests of QCD.

After establishing the existence of gluons and of hard gluon radiation through the observation of 3-jet events, it was consequential to verify if also 4-jet events, a process predicted by second and higher order perturbation theory, can also be seen at PETRA. In a study of event shape distributions that are sensitive to non-planar event structures, JADE indeed found first evidence for the "Observation of Four - Jet Structure in e^+e^- Annihilation at $\sqrt{s} = 33$ GeV" [52]. The energy flow of an event with four well separated jets, later observed at the highest PETRA energies, is displayed in Figure 11.
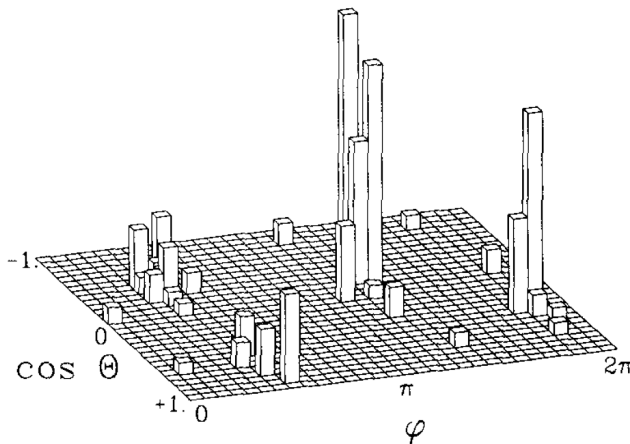
Fig. 11 Energy flow in the ϕ - $\cos\theta$ - plane of an event measured with the JADE detector at 46.7 GeV c.m. energy. ϕ is the angle in the plane perpendicular to the beamline and θ is the angle with respect to the beamline. The highest bin corresponds to an energy of 6 GeV[53].

The observed production rates of 4-jet like events, however, appeared to be larger than predicted by the calculations and models based on QCD in second order ($\mathcal{O}(\alpha_s^2)$) perturbation theory. This motivated to perform further and more detailed studies of jet production rates and their dynamics, and to test QCD to a more detailed level.

For this purpose, JADE developed a jet finding algorithm [53] that defines and reconstructs jets in terms of a resolution parameter, the minimal scaled invariant pair-mass $y_{cut} = \min(M_{ij}^2/E_{vis}^2)$ that is allowed for any pair of objects i and j which are considered as resolvable jets, where E_{vis} is the total (visible) energy of all objects of an event[13]. The algorithm is infrared and collinear safe, i.e. it is insensitive to a low-energy or a small-angle splitting of an object. This feature avoids infrared and collinear singularities in perturbative QCD calculations, such that theory, together with the hypothesis of *local parton-hadron duality* [54], provides reliable and well defined predictions of the expected dynamics of hadron jets, and thus the means for precise experimental verifications of QCD.

In "Experimental Studies on Multijet Production in e^+e^- Annihilation at PETRA Energies" [53], the most highly cited publication of JADE and of all PETRA experiments, JADE introduced this jet algorithm and published 2-, 3-, 4- and 5-jet event rates as a function of the jet resolution parameter y_{cut}, in the c.m. energy range of 14.0 to 46.7 GeV. The data were compared with model calculations [55] based on $\mathcal{O}(\alpha_s^2)$ QCD predictions [56], and with a parton shower model [57] including multiple gluon radiation according to leading logarithmic approximations (LLA) and soft gluon coherence effects [58].

The measured 2- and 3-jet rates and their dependence on the size of the jet resolution were well described by the $\mathcal{O}(\alpha_s^2)$ QCD model, but its deficiency in describing 4- (and higher) jet events was further substantiated. The QCD shower model described 4- and 5-jet rates well but fell short of reproducing the relative rates of hard 3-jet events. Both these observations led to further developments and optimisations of the underlying QCD calculations and their implementation in QCD models, see e.g. [59, 60] and references quoted therein.

Finally, two years after the shut-down of the PETRA collider, JADE extended its studies of jet production rates using the full data statistics in the energy range from 22 to 46.7 GeV [44], and published the first "Experimental Investigation of the Energy Dependence of the Strong Coupling Strength". Instead of extracting values of $\alpha_s(q)$ at different c.m. energies q, which usually suffer from large systematic uncertainties due to the modelling of the hadronisation process, the energy dependence of 3-jet event production rates R_3 was analysed.

According to QCD perturbation theory, the 3-jet rate defined by the JADE jet algorithm is proportional to the strong coupling. In second and higher perturbative order, the prediction reads $R_3(q) = C_1\alpha_s(q) + C_2\alpha_s^2(q) + ...$, whereby the coefficients C_n are - for a given value of y_{cut} - independent of the energy scale q, and the energy dependence of R_3 is solely determined by that of the coupling strength α_s. Additional effects, induced by the hadronisation process,

---

[13]The algorithm starts with calculating the scaled invariant pair masses y_{kl} for all pairs of particles, and replaces the pair with the smallest value of y_{kl} by a new object with four-momentum $p_k + p_l$. The procedure is repeated until all pair masses exceed the value of the resolution parameter y_{cut}.
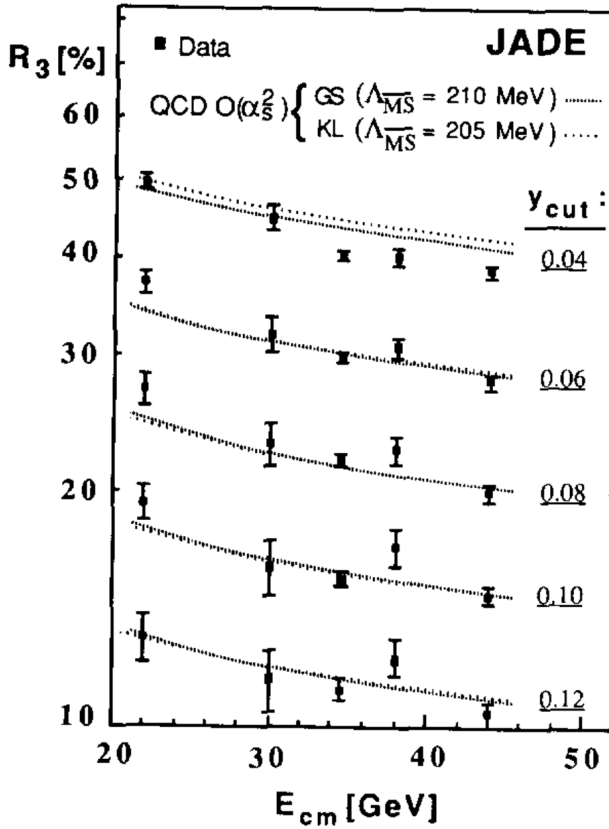
Fig. 12 Three-jet event rates at different centre of mass energies for various values of the jet resolution parameter y_{cut}, together with the predictions of the complete second-order perturbative QCD calculations of Gottschalk and Shatz (GS) and of Kramer and Lampe (KL).

are demonstrated to be small and energy independent, in regions of sufficiently large values of $y_{cut} \geq 0.06$ and for c.m. energies above 22 GeV.

The measured energy dependence of R_3, in the c.m. energy range from 22 to 46 GeV and for different fixed values of y_{cut}, is shown in Fig.12. Without any further correction or modelling of hadronisation effects, the data are well described by the predictions of $\mathcal{O}(\alpha_s^2)$ perturbative QCD [61, 62]. This applies to both the absolute rates at different values of y_{cut} and their observed energy dependence. The significance for discriminating an assumed energy independence of R_3 and thus, of constant α_s, is at the level of 4 standard deviations.

Due to its applicability in both experiment and theory and its relative insensitivity to hadronisation and nonperturbative effects, the JADE jet algorithm was adopted by many experiments at e^+e^- colliders to come, in particular those at TRISTAN ($\sqrt{s}$ around 60 GeV) of the Japanese KEK laboratory and at the Large Electron Positron collider LEP ($\sqrt{s} = 89$ to 214 GeV)

at CERN. Later on, in the 1990s and with the experience of the LEP data, this class of algorithms was further developed, keeping the basic idea of successive clustering of particles but modifying the definition of the jet resolution, thereby enabling the application of refined theoretical methods (see e.g. [63]).

4.2 Hadronisation Phenomenology

Colour-charged quarks and gluons do not exist as free particles. Instead, they convert into colour-neutral hadrons. This process cannot be quantified nor calculated by QCD perturbation theory, but for now must be parametrised by means of phenomenological hadronisation, or fragmentation, models.

At the time of early PETRA operation, fragmentation of fast moving quarks (and antiquarks) was commonly described using the Field-Feynman model [64], generating particles (mesons) that acquire a fraction z of the longitudinal momentum of the primary quark and a limited transverse momentum ($p_\perp$) around the initial quark, statistically parametrised by a phenomenological fragmentation function $f(z)$ and a gaussian $p_\perp$ distribution with a width parameter σ_q.

The model of Field and Feynman was extended to also cover $q\bar{q}g$ final states, where gluons were first split into a secondary $q\bar{q}$ pair, with subsequent Field-Feynman like hadronisation of these secondary quarks [65][66]. An alternative approach to hadronise $q\bar{q}g$ final states was introduced by the Lund group [67], where fragmentation does not proceed along the directions of the outgoing quarks, but instead along string-like colour flux lines between the primary quark and the gluon, and the primary antiquark and the gluon.[14]

This QCD-inspired treatment of colour-charged quarks and gluons predicts a depletion of particles in the region between the primary quark and antiquark, compared to the regions between the (anti)quark and the gluon. The "independent" gluon fragmentation models [65, 66] would not predict such a depletion.

In addition to the string-effect and its QCD-inspired interpretation, QCD predicts the general properties of gluon-initiated jets to be different from jets initiated by quarks. Due to the larger colour-charge of gluons and the effects of gluon-self-coupling, particles from gluon jets are expected to exhibit a broader distribution of transverse momenta $p_\perp$ w.r.t. the principal (gluon-) jet direction.

4.2.1 String Fragmentation and Differences between Quark- and Gluon-Jets

The prediction of the "string-effect" was corroborated, for the first time, in "Experimental study of jets in electron-positron annihilation" [68] by JADE, and manifested later in a more detailed study of "Particle Distributions in 3-Jet Events Produced by e^+e^- Annihilation" [69], see Figure 13, and in a

---

[14]In 1981 Bo Andersson approached a member of the JADE collaboration with his idea of the "LUND-string" and how to test it. The studies started without delay and became the thesis subject of Rolf Felst's student Alfred Petersen.
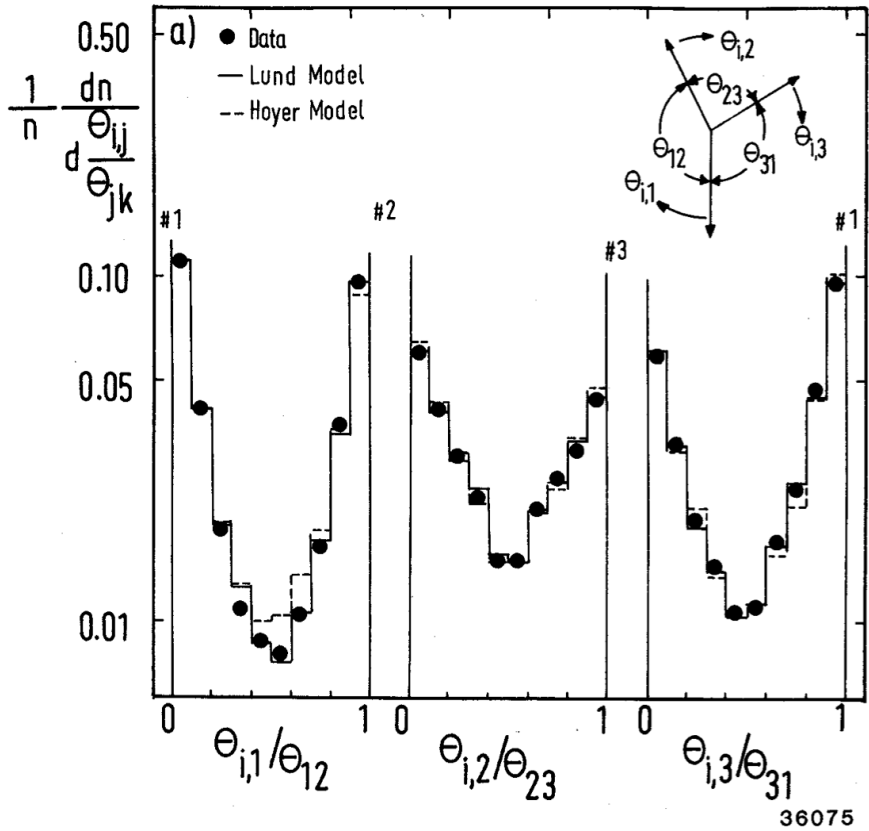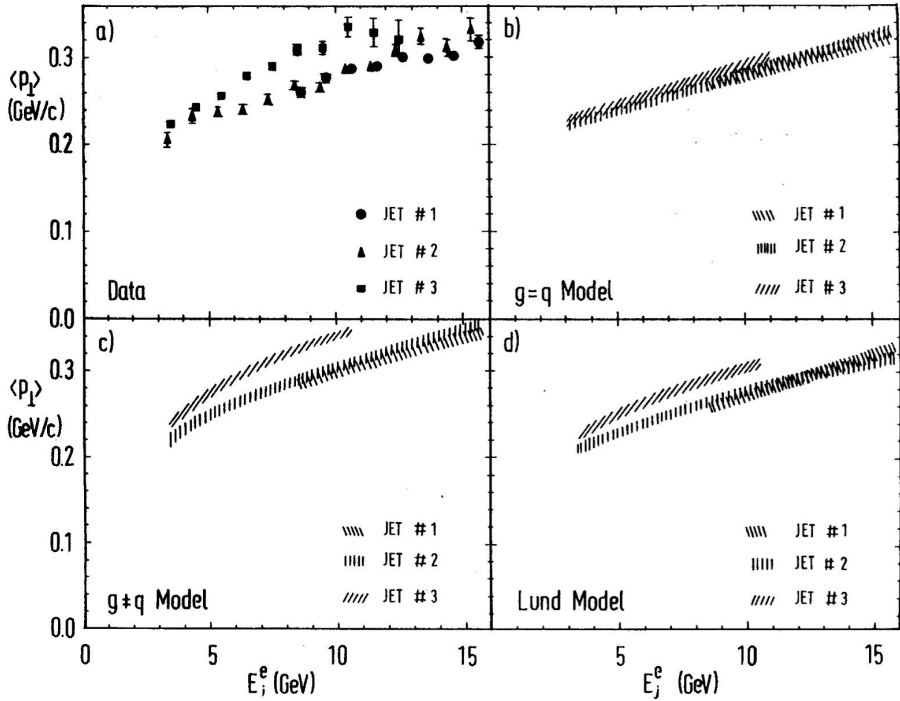
Fig. 13 The average charged and neutral particle density in the angular regions between the jet axes, normalized by the total number of particles, versus $\Theta_{i,j}/\Theta_{jk}$. The data are shown together with predictions of the Hoyer and the Lund model. Jets are ordered according to their energies, $E_1 \geq E_2 \geq E_3$, so that jet #3 is the gluon initiated jet, and jets #1 and #2 are the quark and antiquark jets most of the time.

further "Test of Fragmentation Models by Comparison with Three Jet Events Produced in $e^+e^- \to$ Hadrons" [70]. The string effect appears as a depletion of particles in the region between the two highest energetic jets of 3-jet events.

Evidence for the string effect was more than just of academic importance: experimental determinations of the strong coupling α_s - a fundamental parameter of nature like the electromagnetic coupling and fine structure constant α - resulted in significantly different values of α_s when data were corrected for hadronisation effects using these fundamentally different types of models, see e.g. [71]. The experimental evidence for the string effect was finally confirmed by TASSO [72] and by the TPC/2γ Collaboration [73] at the PEP collider at the Stanford Linear Accelerator Center. Furthermore, it was demonstrated - in the theoretical framework of local parton-hadron duality - that coherence of soft gluon emission provides the QCD explanation of the string effect

observed in experiments [74]. Since that time, the phenomenology of independent jet fragmentation is depreciated and the concept of string hadronisation has become a standard in modelling hadronic final states at all generations of particle colliders following the days of PETRA.

Fig. 14 The average transverse momentum of the charged and neutral particles within a jet relative to the jet axis, for the three jets as a function of the jet energy for (a) the experimental data with $E_{cm} > 29$ GeV, and (b), (c), (d) for the prediction of the q = g model, the q $\neq$ g model ($\sigma_q = 330$ MeV, $\sigma_g = 500$ MeV), and the Lund string fragmentation model, respectively.

In a further study of 3-jet events, comparing the average transverse momentum $\langle p_\perp \rangle$ of particles in the lowest energy jet with those in the other jets, JADE found "Experimental evidence for differences in $\langle p_\perp \rangle$ between quark jets and gluon jets" [75], see Fig. 14. At a given jet energy, the average $p_\perp$ of particles within the lowest energy jet of a 3-jet event is larger than the average $p_\perp$ of the other jets.

The string fragmentation model reproduces the observed effect, while for independent jet fragmentation models, parametrised according to Field and Feynman, one needs a σ_q of about 300 MeV for quark jets and of about 500 MeV for gluon jets to explain these data. However, even with increased σ_q for the gluon jet, independent jet fragmentation models are not able to reproduce the string effect as observed in Fig. 13.

4.2.2 Charged Particle, Neutral Kaon and Baryon Production

Most analyses of e^+e^- annihilation processes into quarks and gluons require a precise knowledge and modelling of the fragmentation process. These models contain a number of free parameters and parametric functions, which are not given by theory, but must be adjusted to provide an optimal description of the data. In these models the multiplicity of charged particles is essentially given by fragmentation functions, determining the relative particle momenta along the jet direction, and by the fraction of pseudoscalar to vector particles produced.

In a study "Charged Particle and Neutral Kaon Production in e^+e^- Annihilation at PETRA" [76], JADE determined experimental constraints on the parameters controlling these model properties, in a previously unknown c.m. energy range from 12.0 GeV to 36.7 GeV.

As one example, the energy dependence of the mean charged particle multiplicity is shown in Fig. 15. It is found to rise faster than logarithmically with energy. The data can be satisfactorily fitted by functions predicted by perturbative QCD, and also by fragmentation models based on first order QCD with fragmentation parameters properly adjusted.
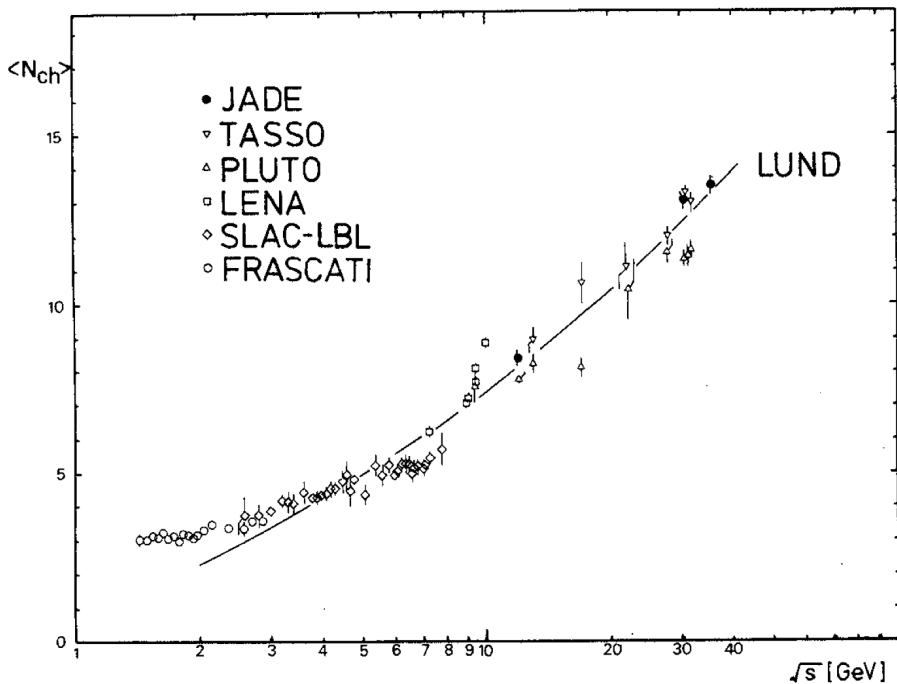
Fig. 15 Mean charged particle multiplicity as function of the centre-of-mass energy $\sqrt{s}$. Only statistical errors are shown. Decay products of neutral kaons are included. The curve is obtained using the Lund model.

Distributions of the charged particle multiplicity at different c.m. energies exhibit KNO scaling [77]. These distributions are well described by the Lund model, while the independent fragmentation model of Hoyer et al. fails in this respect at c.m. energies above 30 GeV.

The observed number of neutral kaons per event varies from 1.1 at $\sqrt{s} = 14$ GeV to 1.5 at $\sqrt{s} = 35$ GeV and can be matched by the fragmentation model with a relative suppression factor $\gamma_s = 0.27 \pm 0.03 \pm 0.05$ of strange quarks being produced in the fragmentation process - to be compared to an expected factor of 1 if strange quarks had the same mass as the light u and d quarks, and to 0.5 as assumed in the original Field-Feynman model.

The production of baryons, bound states of three quarks or three anti-quarks, was not modelled in early versions of fragmentation models, and details about baryon production were scarce in the early times of PETRA opera-tion. In a study of "Baryon Production in e^+e^- Annihilation at PETRA" [78], JADE selected candidates of antiprotons $\bar{p}$ in the momentum range from 0.3 to 0.9 GeV/c, through their specific energy loss (dE/dx) measured in the cen-tral jet chamber. In addition, candidates for antilambdas ($\overline{\Lambda}$) were selected through their decay $\overline{\Lambda} \to \bar{p}\pi^+$. About 20% of all hadronic events contained a $\bar{p}$, either directly produced in the fragmentation process or from hyperon or reso-nance decays, and 7% had a $\overline{\Lambda}$. The data indicated an angular anticorrelation of baryon-antibaryon pairs.

## 4.3 Electroweak Precision Tests

4.3.1 Total Cross Section

The ratio of the hadron production cross section to the lowest order pointlike QED cross section, $R = \sigma_{had}/\sigma_{pt}$, with $\sigma_{pt} = (4\pi/3s)\alpha^2$, is a fundamental quantity in e^+e^- interactions, as it provides important information about the number of quark flavours which are produced in the accessible energy range. R is calculated in the quark-parton model as $R = 3\Sigma_q Q_q^2$, where Q_q is the quark electric charge, and the summation runs over all the produced quark flavours q. If the threshold for pair production of new charge 2/3 (1/3) quarks is passed, R is increased by about 36% (9%). The importance of the R measurement was enhanced by theoretical considerations that predicted the existence of a yet undetected, sixth quark, i.e. the top quark which was assumed to become accessible at PETRA. Also, if quarks would have structure, a deviation from a constant R should be observed.

The value for R is modified when including the lowest order QCD correc-tions and electro-weak effects: QCD corrections to first order increase R by about 5% at $\sqrt{s} = 30$ GeV. The effect of the weak neutral current is energy dependent. It increases R by 1.5% at $\sqrt{s} = 37$ GeV.

Therefore, from early on all PETRA experiments focused on the measure-ment of the total cross section. During the lifetime of the experiment, JADE issued three publications covering this topic [21, 79, 80].

For these measurements, an important feature of the JADE detector was its sensitivity to charged particles and photons over 97% and 90% of the full solid angle, respectively. In a first step, multihadron ($e^+e^- \rightarrow$ hadrons) events were identified by a "charged particles trigger" in combination with a "shower energy trigger". Both triggers showed a considerable overlap.

In a second step, multihadron events were selected offline by a set of criteria which eliminated various sources of background, such as $e^+e^- \rightarrow e^+e^-$ events (Bhabha scattering), τ pair production or cosmic ray background, by applying cuts on the momentum balance as well as on the visible energy of events. The luminosity was determined from small angle Bhabha scattering detected by the end cap counters.
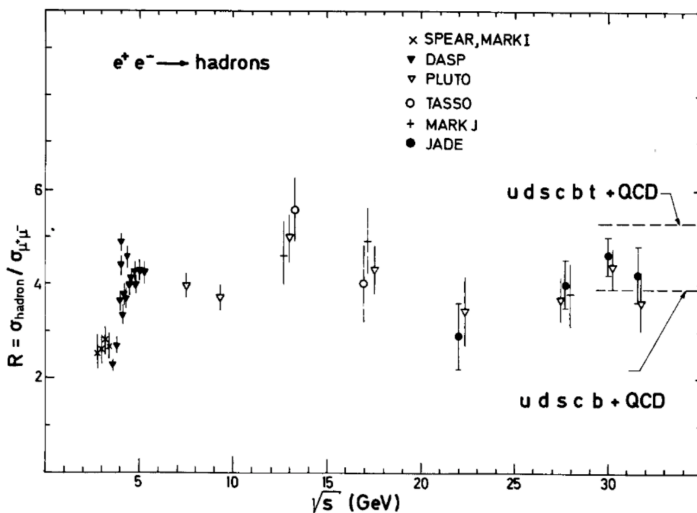
Fig. 16 Ratio R of the hadronic to the point like cross section as a function of the centre-of-mass energy $\sqrt{s}$. The predictions with and without a top quark are also shown.

The values for R, obtained from the data collected during the first year of PETRA operation, a total of 357 multihadron events, are shown in Fig 16, together with data from other experiments. The errors are statistical only. Assuming only u, d, s, c and b quarks, the naive quark-parton model predicts $R = 11/3$. This value is increased from 3.66 to 3.9 by the inclusion of QCD corrections. The measured values of R are compared with the expected R in case of the production of a charge 2/3 top-quark pair. There is no evidence in the data for the production of a new quark flavour with a charge of 2/3.

In a second paper [79], R values were measured in the center of mass energy range between 12.0 and 36.4 GeV with systematic errors of typically $\pm 3\%$. This analysis was based on an integrated luminosity of $38pb^{-1}$ accumulated in 1979-1981. About 15 000 multihadron events were obtained.

The number of measured multihadron events was corrected for acceptance, calculated by a Monte Carlo simulation. In this simulation, the Lund model [55]

was used together with the initial state radiative corrections of Berends and Kleiss [81]. The parameters in the model were chosen such that the measured and calculated charge multiplicity and neutral kaon production agreed. The simulation also showed that the fraction of events lost by the hardware trigger was less than 1% with a negligibly small error.

The data were consistent with a constant R in this energy range with an average value of 3.97 ± 0.05 (statistical and point-to-point systematic error) ± 0.10 (overall normalisation error). Corrections due to QED process of $\mathcal{O}(\alpha^4)$ or higher were not included. The data excluded a step in R of $\Delta R_0 > 0.29$ at the 95% confidence level, ruling out the pair production of a charge 2/3 quark with mass between 7.5 and 17.5 GeV.
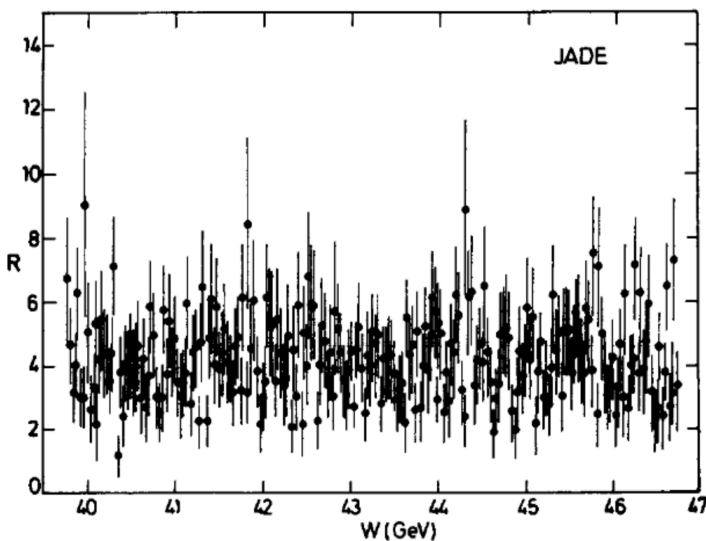
Fig. 17 The ratio R measured between $\sqrt{s} = 39.79$ GeV and 46.78 GeV during a scan in steps of 30 MeV in order to find narrow resonances of bound $t\bar{t}$ states .

The third publication [80] reported the results of the total cross section measurements in the highest energy range explored by PETRA, between 39.79 and 46.78 GeV, and summarised the results obtained in the entire PETRA energy range. The specific goal of the high energy run was the search for the top quark by a step-wise increase of the energy. Toponium - the lowest mass bound state of a top- and an antitop-quark - would locally enhance the total cross section by a factor of 2 to 3.

The R-values of this scan are shown in Fig. 17 as a function of the c.m. energy. The overall normalisation error is 3.3%, the point-to-point error ± 1%. The data are consistent with a constant value of R in the scanned energy range. The average value is $R = 4.13 \pm 0.08 \pm 0.14$, where the second error is the overall normalisation error.
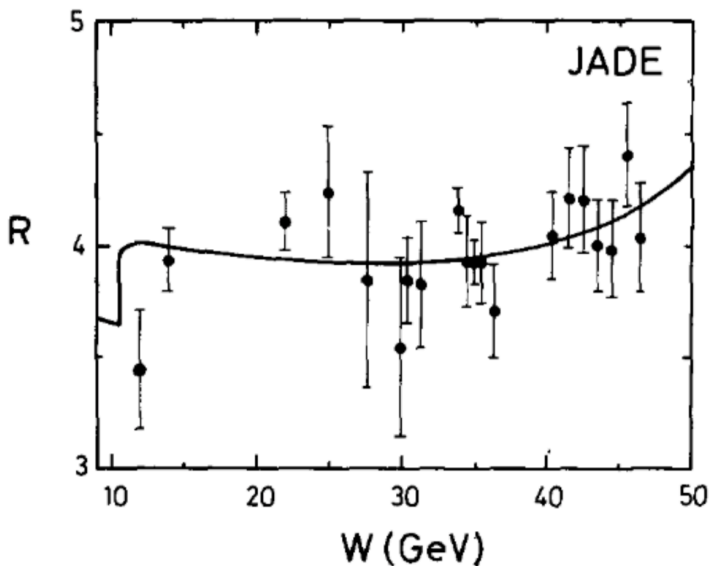
Fig. 18 Summary of the ratio R averaged in bins of 1 GeV c.m. energy. The curve represents the best fit to the standard electroweak interaction model with QCD corrections, with $\alpha_s(30\ GeV) = 0.20$ and $\sin^2\theta_w = 0.23$.

Looking at the entire data sample collected by JADE in the time between 1979 and 1986 in the energy range from 12 to 46.8 GeV one obtains Fig. 18. The plot clearly exhibits two effects, the absence of the top quark (later found at a much higher mass of 175 GeV), and the good description of data by a fit to the standard electroweak interaction model, yielding $\sin^2\theta_W = 0.23^{+0.03}_{-0.04}$ for the weak mixing angle θ_W, and exhibiting the tail of the rising cross section of real Z^0-boson production[15].

4.3.2 Charge asymmetry in $e^+e^- \rightarrow \mu^+\mu^-$

At the highest PETRA energies the standard electro-weak theory predicts sizeable interference effects between electromagnetic and weak neutral currents which should manifest themselves in angular asymmetries. At low energies, such processes are expected to be well described by QED alone, if contributions up to $\mathcal{O}(\alpha^3)$ are included.

In a first publication [84], the angular distribution and the s dependence of the total cross section for the process $e^+e^- \rightarrow \mu^+\mu^-$ was measured by JADE at centre of mass energies in the range $12.0 \leq \sqrt{s} \leq 36.8$ GeV. The measurement was made using the jet chamber to measure directions, momenta and charges of the outgoing particles. Separation of muon pair candidates from background processes was achieved with the help of time-of-flight (TOF) counters, lead glass shower counters, and the muon filter.

---

[15]The Z^0 boson was discovered in 1983 at CERN's Super Proton Synchrotron, at a mass of $\sim$92 GeV/c^2 and a decay width of $\sim$2.5 GeV/c^2 [82, 83].

Springer Nature 2021 LaTeX template

The angular distribution of the positive muon for the data above a c.m. energy of 25 GeV showed, after extrapolation to the full solid angle, a clear forward-backward asymmetry of $A = -(11.8\pm3.8\pm1)\%$, where the first error is statistical and the second one systematic. This asymmetry demonstrates sizeable interference effects between electromagnetic and weak neutral currents, thereby excluding pure QED by three standard deviations while agreeing well with the standard model SU(2) x U(1) of Glashow, Salam and Weinberg, which predicts an asymmetry of $A = -7.8\%$ for the same angular acceptance.

An update of these measurements based over a larger energy range, up to 42 GeV and on higher statistics [85], showed how the forward-backward asymmetry increased with the center of mass energy, in full agreement with the prediction of the Standard Model, see Fig. 19.
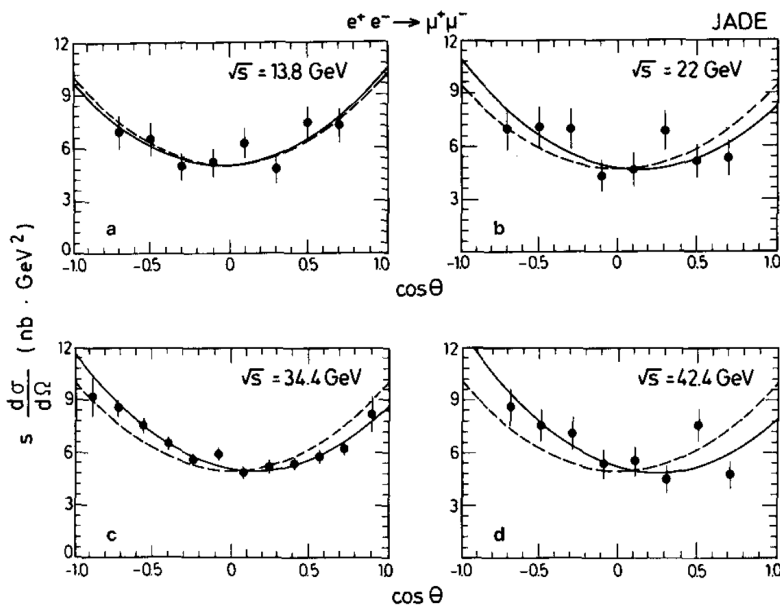
Fig. 19 Angular distributions of $e^+e^- \to \mu^+\mu^-$ for four c.m. energies. The dashed lines are symmetric fits $f(\theta) \propto (1+\cos^2\theta)$, the full lines are fits allowing an additional asymmetry $f(\theta) \propto (1 + \cos^2\theta + B\cos\theta)$ [85].

4.3.3 Charge asymmetry in $e^+e^- \to b\bar{b}$

Electroweak interference effects in e^+e^- collisions in the energy range of PETRA are expected to also lead to a forward backward asymmetry in the emission of the final state quark pairs. This asymmetry can be used to measure the electroweak charges. The first statistically significant asymmetry measurements had been performed for purely leptonic final states for two main reasons: (a) Although the interference effects for quarks are expected to be large, the

separation of the various flavours has been a problem. (b) The determination of the primary quark charge is challenging.[16]

The JADE paper "A Measurement of the Electroweak Induced Charge Asymmetry in $e^+e^- \to b\bar{b}$" [86] describes a method for partially overcoming these problems for b-quarks, thus enabling the measurement of the forward-backward charge asymmetry for the process $e^+e^- \to b\bar{b} \to \mu^{\pm}+$ hadrons.

The flavour separation is based on three observables derived from the kinematics of selected hadronic events which contain an identified inclusive muon: 1) the jet transverse mass, 2) the muon transverse momentum, and 3) the overall transverse momentum imbalance, i.e. the missing transverse momentum. In all three cases, the momentum components are measured transverse to the major axis of the event sphericity ellipsoid (see e.g. [87]) which defines the jet axis. The transverse mass is obtained by summing the transverse momentum components of all charged and neutral particles (except the muon).

Monte Carlo simulations showed that the probability distribution functions of these quantities exhibit a good discrimination between light quarks (uds) and the heavier quarks, c and b [88]. The simulation also reproduced the detailed shapes of the measured spectra of the observables, indicating that they are well understood and the JADE detector is sufficiently hermetic to allow these variables to be used successfully.

The data used for this analysis were collected up to the summer of 1983 and correspond to an integrated luminosity of 76 pb^{-1}. From the sample of multihadron events with PETRA beam energies above 15 GeV, 1780 events were selected containing a muon candidate together with hadrons which satisfied the standard JADE visible energy and longitudinal momentum balance criteria. The average c.m. energy of this sample was 34.6 GeV.

The polar angle θ of the final state $q\bar{q}$ system was estimated using the sphericity axis. If the event had a μ^- in the direction of the e^- or a μ^+ in the direction of the e^+ beam, then $\cos\theta$ was defined to be positive. Using the three variables described above, a likelihood analysis was used to determine the numbers for forward and backward b events: $N_b^F = 114.6 \pm 12.5$, $N_b^B = 191.3 \pm 16.2$. The angular distribution of these events is shown in Fig. 20, exhibiting a clear forward-backward asymmetry.

The ratio of forward-backward events yields, after correcting for acceptance, an asymmetry for b-quarks of $A_b = (-22.8 \pm 6.0 \pm 2.5)\%$. The Standard Model prediction for the b asymmetry is -25.2%. This number is only 2.8 times that of the $\mu^+\mu^-$ asymmetry (and not 3 times as expected from the

---

[16]Due to the high quality tracking, in rare cases the full decay of the b-hadrons could be reconstructed. Dieter Haidt, senior scientist at DESY came to Hamburg after having worked on the discovery of neutral currents at the Gargamelle bubble chamber at CERN. He recalls: *My choice to join JADE rather than one of the other PETRA groups was based on the fact that the jet chamber was nearest to a bubble chamber and my experience may perhaps be to the benefit of the collaboration: Once I found an outstanding event and presented it to the JADE meeting as a complete cascade decay of a B-hadron, i.e. b → c with subsequent c → s and finally manifesting itself as a K in the final state. Rather than applause I got the concise remark by Orito: "Come back, if you have a thousand of such events".* This story is typical for the rigorous quality requirements in JADE, and also demonstrates the change of paradigm from optical to electronic recording and analysis of particle reactions.
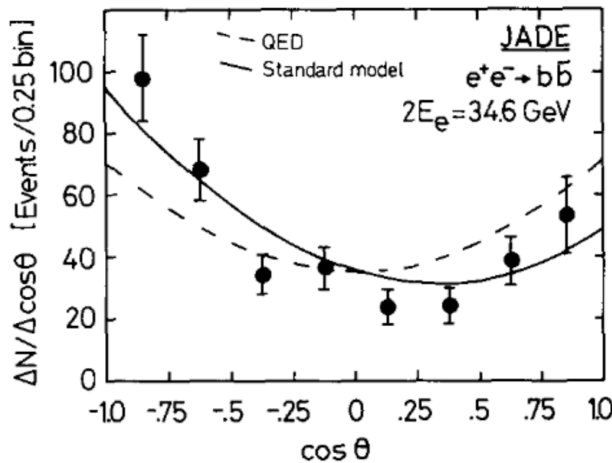
Fig. 20 The extracted angular distribution for $b\bar{b}$ events. The dashed curve is proportional to $1 + \cos^2\theta$ (no asymmetry) and the solid curve is the prediction of the standard model at 34.6 GeV.

ratio of charges) due to the significant mass of the b quark. The measurement is in good agreement with this prediction.

This measured asymmetry can be used to determine a value for the ratio of the b-quark's weak axial (a_b) to the electric (Q_b) charge of $a_b/Q_b = -2.71 + 0.71$ (stat) $+ 0.30$ (syst). Assuming $a_b = a_c = -1$, the result determines the b electric charge: $Q_b = -0.37^{+0.13}_{-0.07}$ (stat.) ± 0.03 (syst.), which is consistent with charge -1/3 for the b quark.

4.4 Photon Structure Function

Since the early 1970s, deep inelastic scattering processes of highly virtual photons γ^* (with $Q^2 >> p^2$) on a target real photon ($p^2 \approx 0$), Q^2 being the 4-momentum squared of the virtual and p^2 the 4-momentum squared of the real photon, raised significant interest because the structure function of the photon, $F_2^\gamma(x, Q^2)$, was predicted to exhibit features that are quite different from those of the structure function of protons, $F_2^p(x, Q^2)$ - see e.g. [89] for a summary of the development of the field.

In short, such processes can be studied in reactions like $e^+e^- \rightarrow e^+e^- +$ hadrons, where photons radiated off the initial electron and positron transform into a final state of hadrons. Cross sections of such processes at e^+e^- colliders are expressed in terms of photon structure functions $F_2^\gamma(x, Q^2)$ and $F_l^\gamma(x)$, where $Q^2 = 4EE' \sin^2(\Theta/2)$ is the squared 4-momentum transfer, $x = Q^2/(Q^2 + W^2)$, E and E' are the initial and final energies of the tagged highly virtual photon, Θ its polar scattering angle, and W is the invariant mass of the produced hadronic system.

At low Q^2, i.e. a few GeV^2, the photon was commonly described to behave like a vector meson, due to quantum fluctuations of the photon into a meson

with the same quantum numbers. In that case, F_2^γ should show Q^2 and x dependencies similar to F_2^p, i.e. F_2 would decrease, at fixed x, with increasing Q^2 - a feature known as scaling violations.

It was found, however, that at not too small Q^2, the process of $e^+e^- \to e^+e^- +$ hadrons is dominated by the point-like cross section according to the quark-parton model, where the photon fluctuates into a quark-antiquark pair, and F_2^γ is predicted to increase with $\log(Q^2)$ [90]. Furthermore, the x-dependence of F_2^γ can be calculated within the quark-parton model - which is also in contrast to F_2^p, where the x-dependence cannot be predicted but must be determined by experiment. Going beyond the simple quark-parton model and including effects of gluon dynamics, and thus of QCD, the slope of the Q^2-dependence can be calculated and is predicted to depend only on a single scale parameter Λ or, alternatively, the QCD coupling strength α_s.
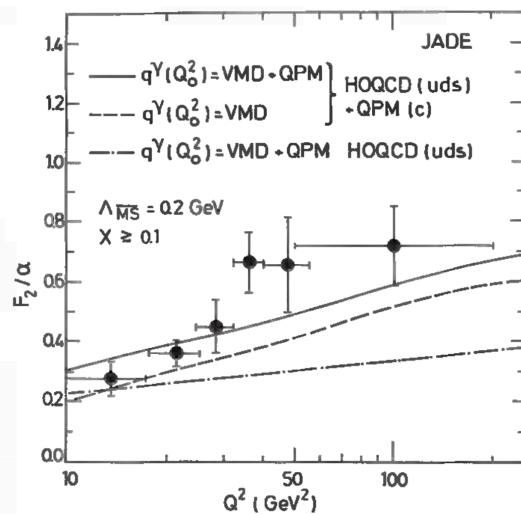
Fig. 21 Measured $F^2(Q^2)$ obtained by averaging F2(x, Q2) over x 0.1. The 5 lower Q2 points are due to the endcap data and the highest Q2 point is due to the barrel data. Solid curve= non- asymptotic HOQCD (u, d, s) +QPM (c) with q1(x, Q) = VMD +QPM and with A = 0.2 GeV. Dashed curve= non-asymptotic HOQCD (u,d,s)+QPM(c) with q(x,Q)=VMD and with A = 0.2 GeV. Dot-dashed curve= non-asymptotic HOQCD (u,d,s) with q'(x,Q)=VMD+QPM and with A=0.2 GeV.

JADE measured and analysed hadron production initiated by two photon interactions, $e^+e^- \to e^+e^- +$ hadrons, where one of the scattered electrons was detected at large angles, with Q^2 ranging between 10 and 220 GeV^2 [91]. The data were compared with non-asymptotic as well as asymptotic QCD predictions. The former takes into account both the contributions from the point-like and vector-meson-like hadronic components of the photon whereas the latter considers only the point-like contribution.

Charged particles were measured with the central drift chamber, photons and electrons were measured in the lead glass shower counters. The tagging of

the electrons was carried out using either the two arrays of endcap lead glass counters which covered the polar angular range 245-500 mrad, or the barrel array of lead glass counters which covered the polar angular range above 609 mrad.

For each hadronic event the Normalised Longitudinal Momentum Balance (NLMB) was calculated. A cut in this variable provides a very efficient suppression of hadronic events from e^+e^- annihilation while hardly affecting hadronic two photon events. The $F_2^\gamma(x)$ functions were determined by unfolding the observed data for detection losses and finite resolution in the JADE detector at values of 24 and 100 GeV^2. They were found to be well described by asymptotic leading order QCD including only the pointlike contribution of F_2^γ, which is calculable in perturbative QCD, and with other leading and higher order QCD calculations and models. For asymptotic leading order QCD, $\Lambda_{QCD} = 0.15(+0.07, -0.04)$ GeV was obtained.

The measurements also show that F_2^γ, averaged over the range $x > 0.1$, increases as a function of Q^2, see Fig. 21. The rise of F_2 with Q^2 is consistent with the combined effect of the $\ln(Q^2)$ dependence of F_2^γ) and the Q^2 dependence of the charm quark contribution, although the data show a slightly steeper slope than the expectation.

5 JADE Data preservation and Software Revival

5.1 Motivation and overview

Long term preservation of data from large scale high-energy physics (HEP) experiments is imperative to preserve the ability of addressing scientific questions at times long after the completion of those experiments. Very often, these data are unique achievements in many scientific respects like energy range, process dynamics and experimental techniques. New, improved and refined scientific questions may require (re-)analysis of such data sets. Investments necessary to repeat past experiments would exceed the efforts of data preservation by far.

The main reasons driving the quest for data preservation are (see e.g. [92]):

- long term completion of the scientific program,
- data re-use for new and advanced studies,
- training, education and outreach.

The scientific motivation for re-using and re-analysing data from past experiments is given by:

- the availability of new theoretical input in terms of increased precision, advanced models or new predictions;
- new and improved analysis techniques;
- the desire to perform cross-checks between different experiments.

After the shut-down of the PETRA in 1986, collaborative analyses of JADE data and publication of results continued with decreasing pace and came to an end by 1990/1991. The data were first moved to a few thousand archive tapes, later to a storage place outside the computing centre, and finally disposed of when the IBM main frame computer was phased out in 1997. The source code of the JADE software framework was collected and stored on private computer accounts which were maintained on the IBM main frame until 1997.

The JADE collaboration had no plan for further data preservation and future use of their data. Private initiatives for long-term preservation started in 1995/1996 at DESY, when Jan Olsson at DESY organised to copy the JADE data to modern and more efficient data carriers, and to preserve the JADE software libraries [93].

Driven by the desire to re-analyse JADE data in terms of much advanced QCD calculations and Monte Carlo models, the resurrection of the JADE software and its usability on modern computer platforms was initiated in 1996/1997, by one of the authors (SB), then Professor at RWTH Aachen, and put into practice by Pedro Movilla Fernandez, a diploma- and later PhD-student at Aachen, and by Jan Olsson. This first step of software recovery was completed by 1999. Until 2013, the revived software, running on IBM AIX systems, was actively used for new analyses of the JADE data, resulting in 3 further PhD theses, 10 journal publications and several contributions to international conferences and workshops.

A second and so far last phase of data preservation started in 2015 and has basically been executed by Andrii Verbytskyi at the Max-Planck-Institute at Munich. In this process, the JADE software was migrated to LINUX systems and modern build tools[17].

In March 2022, the members of the JADE collaboration unanimously decided to release all JADE data and software to be publicly accessible as "open data" and maintained within the CERN open data initiative [94]. The implementation of JADE data, software and documentation into this environment is currently in progress.

Digitisation and preservation of documents, auxiliary data and material like publications, technical and internal notes, collaboration meeting protocols, the log-books from the experiment's main control room, photographs from the time of constructing and operating the detector, and manuals describing the functionality of the resurrected software and data, are an equally important heritage to be preserved. Digitised versions of all JADE publications are accessible through public servers like the InSpire HEP data base https://inspirehep.net. Digital copies of most of the other documents mentioned above were collected and are publicly available at the JADE web pages maintained at the Max-Planck-Institute of Physics at Munich, https:

---

[17]Build tools are programs that automate the creation of executable applications from source code.

//www.mpp.mpg.de/en/research/data-preservation/jade. Some of the information, like a list and copies of PhD theses performed with JADE data, still need to be assembled and will be provided in due time.

5.2 Data Preservation

At the end of data taking, the JADE data comprised about 1 TB of raw and reconstructed data[18] - an amount that looks small by standards of the 2020s, but was huge in the 1980s. The data were stored on thousands of IBM tapes with 160 MB capacity, plus similar amounts of Monte Carlo generated data and private data selections.

Space was a problem at the DESY Computer Centre. Data stored on "Machine Room (M) Tapes" were consecutively moved to "Archive (A) Tapes", stored outside of the main computer area, if they weren't used for a while. Data on A-Tapes were deleted if they stayed unused for a certain time, and if there was no response on warning messages issued to the responsible user. This line of action was also applied to software files and libraries - unless they were declared to be "holy" with plausible justification. At this point, by 1990, the JADE data and core software were still secured on A-tapes, while most of the Monte-Carlo generated data had disappeared.

In winter 1991/92, the imminent start-up of the HERA collider required to recover large amounts of physical space and infrastructure for proper handling and storage of the new data to come. The DESY computer centre requested from the PETRA experiments to significantly reduce their stores of A-Tapes. The remaining tapes were packed in big aluminum boxes that could only be moved by fork-lifts, and stored elsewhere at DESY. At this point, the 1 TB of JADE data resided in 23 of these big boxes that were stored away in DESY's Hall 2, and were deleted from the general catalogue.

By 1995, also the space in Hall 2 was needed for other purposes. Again the PETRA experiments were asked to discard their remaining data, or else to arrange for further storage by themselves. In spring 1996, DESY decided to phase out the IBM Mainframe, also implying that the old IBM tapes would soon be history. The responsible JADE experts, still being on-site but involved in other projects like HERA, decided to move all JADE data onto IBM3490 cartridges, thereby reducing the physical volume of the required storage space such that it finally "should fit into a drawer".

Moving the JADE data to modern data carriers also required to rewrite them such that they could be read on any future computer platform. This requirement led to a number of difficulties and problems, some appearing as major obstacles at that time, which had to be overcome and solved. The stories connected to these activities may carry educational messages for future ventures of that type:

JADE used an early version of the Bank Object System data format [95], BOS4. As computer memory and storage was precious in the late 1970s and

---

[18]About 600 GB of raw data ("REFORM"), 335 GB of reduced and reconstructed data ("REDUC1" and "REDUC2"), and 85 GB of specialised physics selection data.
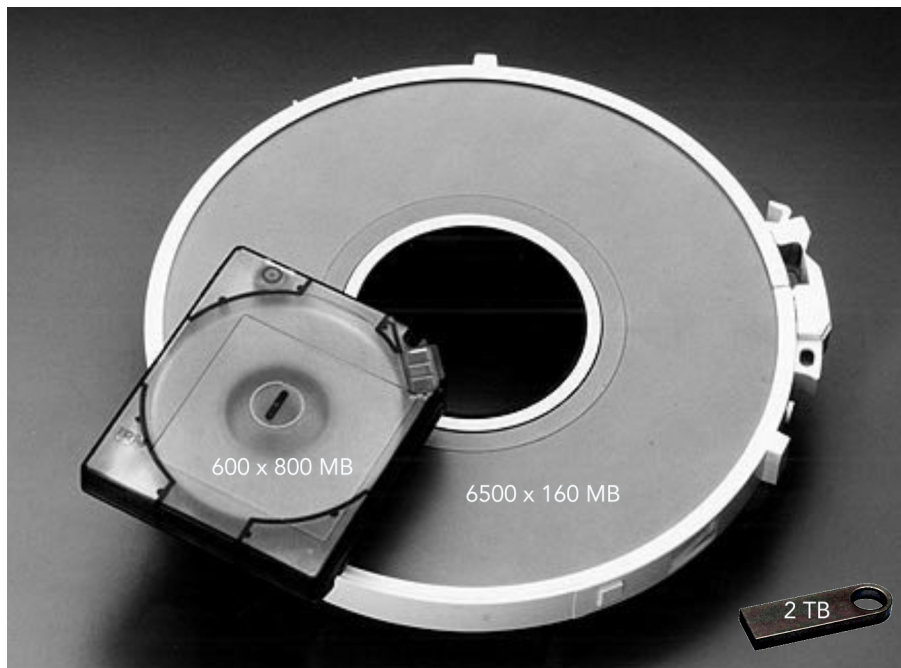
Fig. 22 The JADE data were originally stored on about 6500 IBM tapes, later converted and written to about 600 IBM3490 cartridges, and nowadays conveniently fit onto a single 2 TB USB memory stick.

early 1980s, a rather intricate structure including combinations of I*2, I*4, F, and A-words in the banks was used, even assigning single bits and bytes for various purposes and flags - a fatality if the data are to be processed on machines which use a different byte order than that of the old IBM370. In order to assure platform independence of the data, they were converted using FPACK [96]. FPACK, however, only worked with BOS77, and the BOS4 source libraries - although declared "holy" - no longer existed at DESY, or anywhere else. This initiated a number of archeological initiatives and actions which finally retrieved the original BOS4 source code. The code, however, did not compile any more on any compiler on the IBM mainframe.

Finally, by summer 1997 and having solved all obstacles, the JADE REDUC data plus some special data selections were successfully copied to 600 IBM3490 cartridges. The REFORM raw data were dropped and no longer included in the preservation process. The 3490 cartridges were 6 times smaller than the old IBM tapes, c.f. Fig. 22, and carried 800 MB, i.e. 5 times more data each. A second copy was written to 200 "Exabyte" cartridges (from Exabyte Corporation, a US-American provider of innovative storage solutions), carrying up to 2.5 GB each. These were privately stored in the office of a caring member of JADE. The volume of the size of a drawer was (almost) reached.

In December 2005, the Exabyte cartridge collection travelled to the Max-Planck-Institute of Physics in Munich, conveniently packed in a flight-cabin

trolley, copied to the Max-Planck Computing and Data Facility (MPCDF) as a very small part of the huge data space of the ATLAS experiment at the Large Hadron Collider at CERN, and - due to their "small" size of less than 1 TB - to other discs and cloud services at the MPCDF.

Today, at the time of writing this review, the data fit on a TB USB 3.0 Flash Drive Memory Stick which is available for less than 20 Euro, reducing the drawer-size to the size of a finger tip.

In parallel, since the end of the 1980s, the data of calibrated and fully reconstructed multihadron final states, $e^+e^- \rightarrow$ hadrons, were maintained using a private, compact 4-vector format, ZE4V [97]. In 1996, the ZE4V files were read on the DESY IBM mainframe, converted to ASCII files, and were then stored at the computer centres at RWTH Aachen and - later - at the MPCDF in Garching.

So the original JADE data were preserved. All of the relevant data? Apparently, a small number of files, the JADE luminosity files, escaped preservation and apparently had been lost in the late 1990s. These files contained the reconstructed values of the integrated luminosities of each of the data taking runs, therefore being essential for calculating physical cross sections of processes under study. A worldwide search within the JADE collaboration returned no results, until Jan Olsson found a printed version of the luminosity files at DESY. The printout, however, was on green recycling paper and too faint for scanning and optical character recognition, OCR. Instead, the numbers had to be typed in a tedious effort into a text file. Only 5 typing errors were found and corrected by a checksum routine (that was preserved in the process of software revival, see below), and so even the luminosity files were successfully recovered[19].

5.3 Software Revival

Generation of new detector level Monte-Carlo (MC) generated data sets required the revival of the entire JADE reconstruction and production software. The JADE software source libraries were available, with very few exceptions[20], on the DESY IBM main frame, as private copies since 1991. In 1997, the IBM main frame was phased out and the transition to UNIX platforms was made. The original software, consisting of FORTRAN-IV, but also in part of SHELTRAN and MORTRAN routines, required partial rewriting or conversion to FORTRAN-77; the functionality of parts of the DESYLIB, originally written in assembler code, needed to be emulated with FORTRAN routines.

The reactivation of the JADE software was completed in 1999 [98], and was used for various new analysis projects at RWTH Aachen and at MPI of Physics in Munich, until 2013. The new code versions were validated using various detector-level distributions from original and newly generated MC

---

[19]Jan Olsson's moral on this story [93]: *Always keep a printout as backup! (And never throw papers away).*

[20]The software package for simulating the JADE muon detector escaped long-term archiving and today must be considered to be inevitably lost.
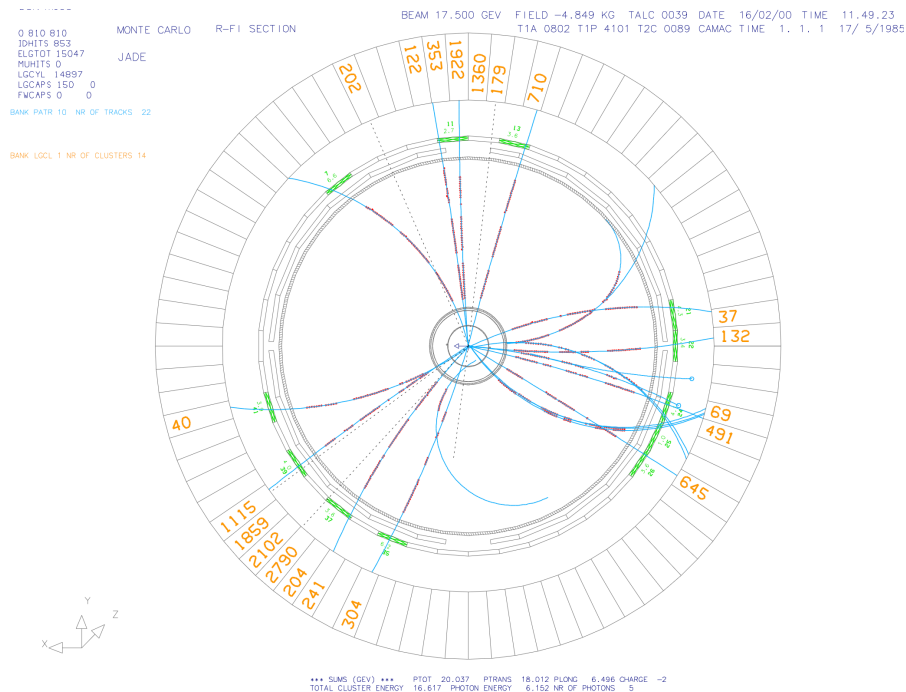
Fig. 23 Monte Carlo generated 3-jet event, reconstructed and displayed using the full revived JADE offline software chain. Note that the display is in colour, a feature that was not available at JADE running times.

event samples. An important tool of validation was the graphical display of JADE events, which was revived to full functionality by emulating the originall graphics and plotting software PLOT10. Since its revival, the event display is capable of using colours, a feature that was not yet available at running time of the experiment, see Fig. 23 for a coloured display of a MC-generated, fully reconstructed hadronic event.

In this first phase of software resurrection and data re-use, the revived JADE software exclusively ran on IBM AIX machines, relying on the fact that these systems utilise the same byte order as the IBM 370 did[21]. It was used to generate new MC-generated data samples, based on modern MC generators, for correction of detector response and resolution, for unfolding data distributions and subsequent comparison with new theoretical calculations. The newly generated MC data sets were converted to the ZE4V format, and physics analyses were then performed using the ZE4V files of both real and MC data.

After 2010, the restriction that JADE data analyses could only be performed on IBM AIX platforms became increasingly inconvenient, due to the

---

[21]The IBM370 as well as IBM AIX machines operated according to the "big-endian" convention, i.e. the highest value byte of a (2- or 4-byte) word had the smallest storage address within the word.

restricted availability of AIX systems and the general move of scientific computing to LINUX systems and modern build tools. The second, and so far final, phase of migrating the JADE software to make it compatible with modern compilers, operating systems and build tools was and still is being executed and maintained by a small "data preservation" group at the Max-Planck-Institute of Physics in Munich, with Andrii Verbytskyi as the main active scientist and computing expert of the group.

This phase of data preservation so far concentrated on using GNU Fortran and Intel Fortran, both supporting I/O with multiple endianness - an essential feature to ensure functionality of the JADE software. In order to avoid dependences on meanwhile unsupported software libraries like CERNLIB [99] and the HIGZ graphic package [100], the required functions were emulated with the help of ROOT [101]. However, the differences in the treatment of graphics in HIGZ and ROOT resulted in instabilities of the detector display program. Therefore, it is expected that JADE software will benefit from ongoing efforts to preserve and re-consolidate CERNLIB.

Due to the portability of the `cmake` build system [102], it is now possible to compile the JADE software not only on LINUX systems but also, for the first time, on MacOSX. The codebase was put in a public GitHub [103] account, which allowed for regular automated builds of the JADE software on these platforms. In order to make modern and generally very complex Monte Carlo generators compatible with the full JADE detector simulation, a utility for converting HepMC [104] events into JADE-readable format was created, thus avoiding the need of multiple different interfaces to MC event generators.

5.4 New Results from Resurrected data

With the resurrection and revival of data and software, the second phase of JADE physics analyses started in 1997 at RWTH Aachen, moving to MPP Munich in 2000. It was based on analysing calibrated and fully reconstructed $e^+e^- \rightarrow$ hadron events, preserved in the compact ZE4V 4-vector format, and on newly generated Monte-Carlo event samples, using modern QCD shower models, processed through the full JADE detector simulation, reconstruction and ZE4V conversion chain. The typical number of data events used in those studies is given in Table 3.

Re-analyses of the JADE data were motivated by the significant increase of knowledge, both in theory and experimental techniques, obtained in the 1990s along with the operation of LEP, the e^+e^- collider at CERN that operated from 1989 to 2000 at c.m. energies from 90 to 214 GeV. Specifically, the main interest focussed on extending advanced studies of hadronic final states and tests of QCD, see e.g. [105] for a review of QCD results from LEP, to the lower energy data from PETRA, namely on

- measurements of new and improved observables, like hadronic event shapes, and application of new and improved jet algorithms,

Table 3 The average centre-of-mass energy $\sqrt{s}$, the energy range, data taking period, collected integrated luminosity L and the number of selected data events, after applying quality selection cuts, as typically used in the second, post-resurrection phase of JADE data analyses.

$\sqrt{s}$ (GeV)	energy range (GeV)	year	L (pb^{-1})	selected events
14.0	13.0-15.0	1981	1.46	1783
22.0	21.0-23.0	1981	2.41	1403
34.6	33.8-36.0	1981-1982	61.7	14313
35.0	34.0-36.0	1986	92.3	20876
38.3	37.3-39.3	1985	8.28	1585
43.8	43.4-46.4	1984-1985	18.8	4374

- scrutiny and application of significantly improved QCD shower Monte Carlo generators,
- application of advanced QCD calculations, in next-next-to-leading order (NNLO) perturbation theory and (next-to-) leading logarithmic approximation (NLLA),
- precision determinations of the strong coupling parameter α_s, and on
- general tests of QCD.

Until 2013, three PhD theses, ten journal publications and several scientific presentations at international conferences and proceedings articles emerged from this second phase of JADE data analyses. The new results were novel or superior to, but always compatible with those that had been previously published by JADE. In the following, two areas of major new insights from these new studies will be reviewed.

5.4.1 New Observables and QCD models: Universal Description of Hadronisation

The first results from the revival phase of JADE were published in 1998, titled *A Study of event shapes and determinations of α_s using data of* $\mathrm{e^+e^-}$ *annihilations at $\sqrt{s} = 22$ GeV to 44 GeV* [106]. It was based on the PhD thesis of P.A. Movilla-Fernandez [107], as the first application and use of the resurrected JADE data and revived software [98]. These first results presented measured distributions of new event shape observables and jet resolution parameters, their comparison with various improved QCD shower models and event generators, and the extraction of values of $\alpha_\mathrm{s}(Q)$ at energy scales of $Q \equiv \sqrt{s} = 14, 22,$ 34 and 44 GeV, based on QCD in next-to-leading order (NLO) perturbation theory plus resummation of next-to-leading logs (NLLA).

None of the new observables, the improved QCD generators, the α_s results at the smallest PETRA energies, nor the resummed QCD calculations had been available at PETRA running time before. Therefore these studies provided a wealth of new and unique results. While measurements of α_s will be further discussed in the next subsection, another aspect of these results shall be emphasised here:
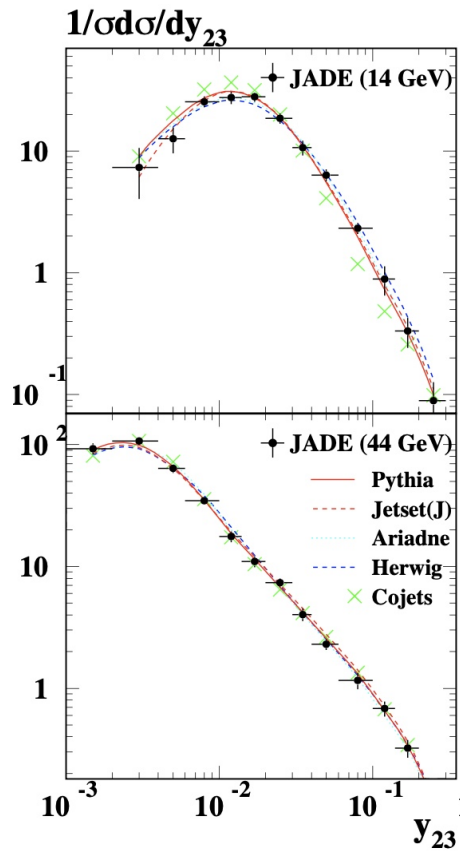
Fig. 24 Measured distributions of y_{23}, the value of the jet resolution where the event changes from a 2-jet to a 3-jet configuration, at the lowest and highest PETRA energies of $\sqrt{s}$ = 14 GeV and 44 GeV, compared with various QCD model calculations using hadronisation parameters obtained from LEP data at $\sqrt{s}$ = 91.2 GeV [107, 108].

At PETRA running time, the low energy data at 14 and at 22 GeV were hardly used, mainly because MC models - at that time, based on LO or NLO QCD only - did not provide satisfactory descriptions of the data, even if the hadronisation parameters of those models were re-tuned at each energy. In contrast, the new JADE studies used the new and improved QCD shower models, which include gluon emission processes to much higher orders, down to much lower invariant masses of $\mathcal{O}(1\ \mathrm{GeV})$, leaving a much smaller phase space for the nonperturbative hadronisation process. Using those shower models with hadronisation parameters optimised to describe the LEP data around the Z^0 pole, leaving all parameters including the QCD scale parameter Λ constant[22], surprisingly resulted in an excellent description of JADE data at all PETRA energies, see Fig. 24. This observation is compatible with the QCD

---

[22]Note that QCD predicts the running and energy dependence of $\alpha_{\mathrm{s}} \sim \log\left(\Lambda/Q\right)$, with Λ being a constant scale parameter.

expectation of a running coupling and an energy-independent description of the hadronisation process.
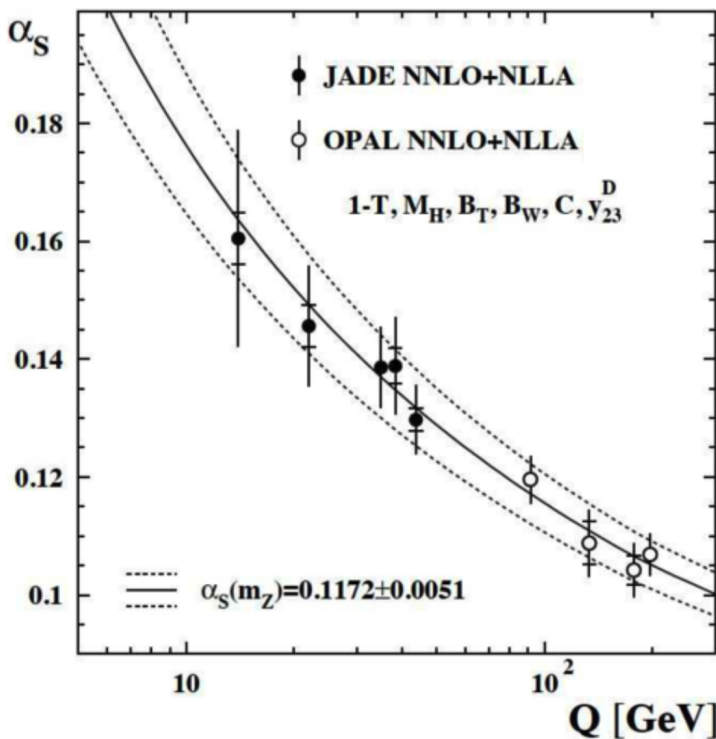
Fig. 25 The values for α_s at the JADE energy points. The inner error bars correspond to the combined statistical and experimental errors and the outer error bars show the total errors. The results from $\sqrt{s} = 34.6$ and 35 GeV have been combined for clarity. The full and dashed lines indicate the QCD prediction of the running coupling based on the combined JADE NNLO result. The results from an NNLO analysis of OPAL data are shown as well [110, 112].

5.4.2 Measurements of α_s and Signature of Asymptotic Freedom

Most of the JADE revival studies explicitly or indirectly dealt with determinations of the strong coupling α_s, owing to a special feature of the JADE data: the wide range of "low" c.m. energies where the QCD prediction of the running coupling is particularly pronounced. Starting with the first publication mentioned in the previous subsection [106], the next step was a precise determination from jet-production rates alone, still in resummed NLO QCD. This was a concerted study of both the JADE collaboration and the OPAL collaboration at LEP, leading to a precise, combined result of $\alpha_s(M_{Z^0}) = 0.1187^{+0.0034}_{-0.0019}$ [109].

The so far "ultimate" determination of α_s from JADE data was based on a study of event shape and jet resolution distributions and the application of the latest, state-of-the-art QCD predictions in complete and resummed NNLO + NLLA perturbation theory [110]. The combined results from six different event shape observables at six JADE centre-of-mass energies from 14 to 44 GeV, assuming the QCD prediction of a running coupling and converting all results the reference energy scale of the Z^0 rest mass, is $\alpha_\mathrm{s}(M_{\mathrm{Z}^0}) = 0.1172 \pm 0.0006(stat.) \pm 0.0020(exp.) \pm 0.0035(had.) \pm 0.0030(theo.)$. This result significantly contributes to and is compatible with the current world average value [111].

More important, the values obtained for the different c.m. energy scales are compatible with the predicted QCD running of the coupling, and with the results obtained from an identical (but separate) analysis of the OPAL data at LEP [112], see Fig. 25. In fact, the JADE results alone exclude the *absence* of running with a significance and confidence level of 99% - a wonderful confirmation and significant strengthening of JADE's early *Investigation of the Energy Dependence of the Strong Coupling Strength* [44], see Sec. 4.1.2.

6 Summary and closing remarks

From today's perspective, JADE was a rather small collaboration, consisting - in total and summed over the active lifetime of the experiment - of about 130 scientists, technicians and engineers from 8 institutions in Germany, England, Japan and the USA [1]. The detector, though, already exhibited key features of today's large experiments in high energy physics, concerning hermeticity and sensitivity to detect and measure the features of charged leptons, photons, charged particles and hadron jets. With only about 50 to 70 collaborators at a given time, the fast planning and construction, the efficient operation, detector maintenance and upgrade, and data analysis was challenging but successfully accomplished. The close and personal collaboration between all members was a unique experience, an enormous pleasure and privilege, and door-opener for many future careers. *JADE is us and we are JADE* is the motto guiding the relation and the still ongoing contact between its members. Fig. 26 shows the members of the JADE collaboration at their reunion at DESY in August 2009.

Together with its friendly competitor experiments CELLO, MARK-J, PLUTO and TASSO, JADE co-discovered the gluon, tested the electro-weak standard model of particle physics, explored many aspects of hadron, lepton and photon production at PETRA, established significant tests of QCD and measurements of the QCD coupling, advanced two-photon physics, performed searches for Supersymmetry and other signals of physics beyond the standard model.

JADE's pioneering and unique contributions were the development and establishment of the JADE jet finding algorithm that was widely used and further developed thereafter, the evidence for string fragmentation, and the evidence for asymptotic freedom of quarks and gluons. The results on the

Fig. 26 The JADE Collaboration at its reunion in August 2009. From left to right: -front row, sitting/bending: Robin Marshall, Klaus Kleinworth, Günter Eckerlin, Rolf Felst, Siggi Bethke, Tomio Kobayashi, Alfred Petersen, Sachio Komamiya, Manfred Zimmer - first row standing: Hanns Krehbiel†, Peter Warming, Wulfrin Bartel†, Uwe Schneekloth, Rolf Heuer, Karlheinz Meier†, Sakue Yamada, Dieter Haidt, Hiroshi Takeda - second row standing: Hans von der Schmitt, Jan Olsson, Farid Ould-Saada, Tatsuo Kawamoto, Hans Rieseberg, Hajime Matsumura, Karl Ambrus, Michael Kuhlen, Austin Ball, Andreas Dieckmann, Harrison Prosper, - back row(s) standing: Jürgen von Krogh, Eckhard Elsen, Joachim Heintze†, Rainer Ramcke†, Norbert Magnussen, Paul Murphy†, Götz Heinzelmann, Henning Kado, Stefan Kluth, Roger Barlow, unidentified person, Hugh McCann, Herbert Drumm, Albrecht Wagner.

energy dependence of α_s and the signature of asymptotic freedom were a decisive element of granting the 2004 Nobel Prize in Physics [113] to the fathers of Asymptotic Freedom of Quarks and Gluons, D.J. Gross, F. Wilczek and H.D. Politzer.

The long-term preservation of JADE data and the revival of the JADE software, the second phase of data analysis starting more than 10 years after shut-down of the experiment, and last not least the decision to save and convert JADE's heritage to "open data", for future unrestricted and public use, are unique key features of JADE. They raised international recognition and serve as motivation for large scale efforts of data preservation in particle physics [114] and beyond.

The question *was it worth the effort?* can be answered with a clear *yes*! Besides being a show-case for similar initiatives currently going on, the scientific output of re-analysing old data with advanced methods and knowledge is more than worth the effort, and will appear in the future, for many cases again. Such initiatives, however, should deserve more concerted effort and resources than was available for the case of JADE. For current and future scientific endeavours that generate orders of magnitude larger amounts of data and software, and that may operate for significantly longer time durations, it will be vital to organise, prepare and profit from data and software preservation already during active life-time of the project, see e.g. [115].

In the case of JADE, retroactive data and software preservation was only possible through personal initiatives of a few motivated and passionate individuals. Jan Olsson, one of the key persons in this process, commented this fact [93] by citing Erich Kästner, a famous German writer, publicist and cabaret artist:

Es gibt nichts Gutes,
ausser man tut es! [23]

May JADE and the awareness for data preservation live forever!

References

[1] The JADE Collaboration: J. Allison^e, K. Ambrus^c, J. Armitage^e, J. Baines^e, A.H. Ball^e, G. Bamford^e, R. Barlow^e, W. Bartel^a, L. Becker^a, A. Bell^d, S. Bethke^c, C. Bowdery^d, T. Canzler^a, S.L. Cartwright^g, J. Chrin^e, D. Clarke^g, D. Cords^a, D.C. Darvill^d, A. Dieckmann^c, G. Dietrich^b, P. Dittmann^a, H. Drumm^c, I.P. Duerdoth^e, G. Eckerlin^c, R. Eichler^a, E. Elsen^b, R. Felst^a, A. Finch^d, F. Foster^d, R.G. Glasser^f, I. Glendinning^e, M.C. Goddard^g, T. Greenshaw^e, J. Hagemann^b, D. Haidt^a, J.F. Hassard^e, R. Hedgecock^g, J. Heintze^c, G. Heinzelmann^b, K.H. Hellenbrand^c, M. Helm^b, R. Heuer^c, P. Hill^f, G. Hughes^d, M. Imori^h, H. Junge^a, H. Kado^b, J. Kanzaki^h, S. Kawabata^a, K. Kawagoe^b, T. Kawamoto^h, B.T. King^e, C. Kleinwort^b, G. Knies^a, T. Kobayashi^h, S. Komamiya^c, M. Koshiba^h, H. Krehbiel^a, M. Kuhlen^b, P. Laurikainen^a, P. Lennert^c, F.K. Loebinger^e, A.A. Macbeth^e, N. Magnussen^b, R. Marshall^g, T. Mashimo^h, H. Matsumura^c, H. McCann^e, K. Meier^b, R. Meinke^a, R.P. Middleton^g, H.E. Mills^e, M. Minowa^h, P.G. Murphy^e, B. Naroska^a, T. Nozaki^d, M. Nozaki^h, J. Nye^d, S. Odaka^h, T. Oest^b, J. Olsson^a, L.H. O'Neill^a, S. Orito^h, F. Ould-Saada^b, G.F. Pearce^g, A. Petersen^b, E. Pietarienen^a, D. Pitzl^b, H. Prosper^e, J.J. Pryce^d, R. Pust^b, R. Ramcke^b, H. Rieseberg^c, P. Rowe^e, A. Sato^h, D. Schmidt^a, U. Schneekloth^b, B. Sechi-Zorn^f, J.A. Skard^f, L. Smolik^c, J. Spitzer^c, P. Steffen^a, K. Stephens^e, T. Suda^h, H. Takeda^h, T. Takeshita^h, Y.

---

[23]engl.: *There is nothing good unless you do it.*

Totsuka[h], H. v.d.Schmitt[c], J. von Krogh[c], A. Wagner[c], S.R. Wagner[f], I. Walker[d], P. Warming[b], Y. Watanabe[h], G. Weber[b], A. Wegner[b], H. Wenninger[a], J.B. Whittaker[g], H. Wriedt[d], S. Yamada[h], C. Yanagisawa[h], W.L. Yen[a], M. Zachara[a], Y. Zhang[a], M. Zimmer[c], G.T. Zorn[f]

[a] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

[b] II. Institut für Experimentalphysik der Universität Hamburg, Germany

[c] Physikalisches Institut der Universität Heidelberg, Germany

[d] University of Lancaster, England

[e] University of Manchester, England

[f] University of Maryland, College Park, MD, USA

[g] Rutherford Appleton Laboratory, Chilton, Didcot, England

[h] International Center for Elementary Particle Physics, ICEPP, University of Tokyo, Tokyo, Japan

[2] The JADE revival group: S. Bethke[a,b], O. Biebel[a,b,c], M. Blumenstengel[a,b], S. Kluth[b], P.A. Movilla-Fernandez[a,b], C. Pahl[a,b], P. Pfeifenschneider[a], J.E. Olsson[d], J. Schieck[b,c] and A. Verbytskyi[b]

[a] III. Phys. Institut, RWTH Aachen, Germany

[b] Max-Planck-Institute of Physics, Munich, Germany

[c] Ludwig-Maximilian-University, Munich, Germany

[d] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

[3] F.J. Hasert et al., Gargamelle Neurino Collaboration, *Observation of Neutrino Like Interactions Without Muon Or Electron in the Gargamelle Neutrino Experiment*, Phys. Lett. **B46** (1973) 138.

[4] S. Glashow, *Partial Symmetries of Weak Interactions*, Nucl. Phys. **22** (1961) 579.

[5] S. Weinberg, *A Model of Leptons*, Phys. Rev. Lett. **19** (1967) 1264.

[6] A. Salam, *Weak and Electromagnetic Interactions*, Conf.Proc.C 680519 (1968) 367.

[7] https://www.nobelprize.org/prizes/physics/1979/summary/

[8] J. J. Aubert et al., E598 Collaboration, *Experimental Observation of a Heavy Particle J*, Phys. Rev. Lett. **33** (1974) 1404.

[9] J. E. Augustin et al., SLAC-SP-017 Collaboration, *Discovery of a Narrow Resonance in* e$^+$e$^-$ *Annihilation*, Phys. Rev. Lett. **33** (1974) 1406.

[10] https://www.nobelprize.org/prizes/physics/1976/summary/

[11] M.L: Perl et al., *Evidence for Anomalous Lepton Production in* e$^+$e$^-$ *Annihilation*, Phys. Rev. Lett. **35** (1975) 1489.

[12] https://www.nobelprize.org/prizes/physics/1995/summary/

[13] S.W. Herb et al., *Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions*, Phys. Rev. Lett. **39** (1977):252.

[14] H. Fritzsch, M. Gell-Mann, H. Leutwyler, *Advantages of the Color Octet Gluon Picture*, Phys. Lett. **B47** (1973) 365.

[15] D.J. Gross, F. Wilczek, *Ultraviolet Behavior of Nonabelian Gauge Theories*, Phys. Rev. Lett. **30** (1973) 1343.

[16] H.D. Politzer, *Reliable Perturbative Results for Strong Interactions?*, Phys. Rev. Lett. **30** (1973) 1346.

[17] J. R. Ellis, M.K. Gaillard, G. G. Ross, *Search for Gluons in* e^+e^- *Annihilation*, Nucl. Phys. **B 111** (1976) 253, Nucl. Phys. **B 130** (1977) 516 (erratum).

[18] G. F. Sterman, S. Weinberg, *Jets from Quantum Chromodynamics*, Phys. Rev. Lett. **39** (1977) 1436.

[19] G. A. Voss, *Petra, An Extension of the Storage Ring Facilities at Desy*, IEEE Trans. Nucl. Sci., **22** no. 3 (1975) 1374;
G.A. Voss, *Der 19 GeV* e^+e^- *Speicherring PETRA*, Phys. Bl. **36** Nr. 9 (1980) 267.

[20] https://inspirehep.net/conferences/963950.

[21] W. Bartel et al., JADE Collaboration, *Total Cross-Section for Hadron Production by* e^+e^- *Annihilation at PETRA Energies*, Phys. Lett. **B 88** (1979) 171.

[22] D.P. Barber et al., Mark-J Collaboration, *Physics with High-Energy Electron Positron Colliding Beams with the MARK-J Detector*, Phys. Rept. **63** (1980) 337.

[23] R. Brandelik et al., TASSO Collaboration, *Properties of Hadron Final States in* e^+e^- *Annihilation at 13 GeV and 17GeV Center-Of-Mass Energies*, Phys. Lett. **B 83** (1979) 261.

[24] V. Blobel (PLUTO Collaboration), *Results from PLUTO at PETRA*, DESY-79/42 (1979).

[25] L. Criegee et al., *PLUTO, a 4π Detector for DORIS*, Proc. 1973 Int. Conf. on Instr. for High Energy Physics, 707 (1973).

[26] M.J. Schachter, CELLO Collaboration, *CELLO: A New Detector at PETRA*, Phys.Scripta 23 (1981) 610; DESY-80/128 (1980).

[27] D.P. Barber et al., *JADE - Proposal for a Magnetic Detector at PETRA*, 1976 (undated and unnumbered, electronic copy available at https://www.mpp.mpg.de/fileadmin/user_upload/Forschung/Fruehere_Experimente/JADE/JADE_Proposal_1976.pdf).

[28] W. Farr et al., *A Drift Chamber System for the Detection of Narrow Particle Jets from* e^+e^- *Reactions*, Nucl. Instr. and Meth. **156** (1978) 283.

[29] B. Naroska, e^+e^- *Physics with the JADE Detector at PETRA*, Phys. Rept. **148** (1987) 67.

[30] W. Farr and J. Heintze, *Drift Chamber Electronics for Time and Pulse Height Measurements with Multiple Hit Capacity*, Nucl. Instr. and Meth. **156** (1978) 301.

[31] wikipedia.org.

[32] H.E. Mills, *Online Event Filtering in the JADE Data Acquisition System.* Nucl. Instr. and Meth. **A247** (1986) 525.

[33] http://heim.bitraf.no/tingo/files/nd/ND-06.008.01A_NORD-10_S_Reference_Manual_June_1977_ocr.pdf

[34] D. Cords, P. Dittmann, R. Eichler and H.E. Mills, *The Data Acquisition System for the JADE Detector*, Nucl. Instr. and Meth. **A245** (1986) 137.

[35] https://nextcloud.mpp.mpg.de/nextcloud/index.php/s/

SLBpNDe7eY2SmeL?dir=undefined&path=%2FJADE%20LogBooks&
openfile=803830

[36] S. Orito *et al.* [JADE], *First Results from JADE*, eConf **C790823** (1979),
52 DESY-79-77.

[37] H. Fritzsch, *Electromagnetism as the Origin of the Lepton and Quark
Masses*, contribution to: 18th Rencontres de Moriond: Electroweak
Interactions, 379-400; MPI-PAE/PTh 25/83, April 1983.

[38] https://www.mpp.mpg.de/en/research/data-preservation/jade

[39] C. Kleinwort et al. [JADE], *A Measurement of the τ Lepton Lifetime*, Z.
Phys. **C42** (1989) 7.

[40] W. Farr, R.D. Heuer and A. Wagner, *Readout of Drift Chambers with a
100-MHz Flash ADC System*, IEEE Trans.Nucl.Sci. **30** (1983) 95.

[41] G. Eckerlin et al., *Front End Processing for a 100 MHz Flash-ADC-
System*, in: Conference on VME-Bus in Physics, 7-8 October 1985.
Geneva, Switzerland (C85-10-07.2), CERN-86-01, p. 147.

[42] https://inspirehep.net called for *find cn jade and date before 1995* on
January 6, 2022.

[43] W. Bartel et al. [JADE], *Experimental Studies on Multi-Jet Production
in* e^+e^- *Annihilation at PETRA Energies*, Z. Phys. C **33** (1986), 23;
doi:10.1007/BF01410449.

[44] S. Bethke et al. [JADE], *Experimental Investigation of the Energy Depen-
dence of the Strong Coupling Strength*, Phys. Lett. B **213** (1988), 235;
doi:10.1016/0370-2693(88)91032-5.

[45] R. Brandelik et al. [TASSO], *Evidence for Planar Events in* e^+e^- *Anni-
hilation at High-Energies*, Phys. Lett. B **86** (1979) 243; doi:10.1016/0370-
2693(79)90830-X.

[46] D.P. Barber et al. [MARK-J], *Discovery of Three Jet Events and a Test
of Quantum Chromodynamics at PETRA Energies*, Phys.Rev.Lett. **43**
(1979) 830; doi:doi.org/10.1103/PhysRevLett.43.830.

[47] Ch. Berger et al. [PLUTO], *Evidence for Gluon Bremsstrahlung in*
e^+e^- *Annihilations at High-Energies*, Phys.Lett.B **86** (1979) 418;
doi:10.1016/0370-2693(79)90869-4.

[48] W. Bartel et al. [JADE], *Observation of Planar Three Jet Events in* e^+e^-
Annihilation and Evidence for Gluon Bremsstrahlung, Phys. Lett. B **91**
(1980), 142; doi:10.1016/0370-2693(80)90680-2.

[49] G. Hanson et al., *Evidence for Jet Structure in Hadron Production by*
e^+e^- *Annihilation*, Phys. Rev. Letters **35** (1975) 1609.

[50] Ch. Berger et al., *A Study of Jets in Electron Positron Annihilation into
Hadrons in the Energy Range 3.I to 9.5 GeV* Phy. Lett. B **78** (1978) 176.

[51] TASSO Collab., talks by R. Cashmere, P. Söding and G. Wolf, Intern,
Conf. on High energy physics (Geneva, June 27-July 4, 1979);
JADE Collab., talk by S. Orito,
MARK J Collab., talk by H. Newman,
PLUTO Collab., talk by Ch. Berger, and
TASSO Collab., talk by G. Wolf, Intern. Symp. on Lepton and photon

interactions at high energies (FNAL, August 23-29, 1979).

[52] W. Bartel et al. (JADE), *Observation of Four - Jet Structure in* e$^+$e$^-$ *Annihilation at* $\sqrt{s} = 33$ *GeV*, Phys.Lett.B **115** (1982) 338.

[53] W. Bartel et al. (JADE), *Experimental Studies on Multi-Jet Production in* e$^+$e$^-$ *Annihilation at PETRA Energies*, Z.Phys.C **33** (1986) 23.

[54] Ya.I. Azimov et al., *Similarity of Parton and Hadron Spectra in QCD Jets*, Z.Phys.C **27** (1985) 65.

[55] T. Sjöstrand, *The Lund Monte Carlo for* e$^+$e$^-$ *Jet Physics*, Comput.Phys.Commun. **28** (1983) 229.

[56] F. Gutbrod, G. Kramer, G. Schierholz, *Higher Order QCD Corrections to the Three Jet Cross-Sections: Bare Versus Dressed Jets*, Z. Phys. C **21** (1984) 235.

[57] B.R. Webber, *A QCD Model for Jet Fragmentation Including Soft Gluon Interference*, Nucl. Phys. B **238** (1984) 492.

[58] G. Marchesini, B.R. Webber, *Simulation of QCD Jets Including Soft Gluon Interference*, Nucl. Phys. B **238** (1984) 1.

[59] S. Bethke, *An Experimental Approach to Optimize and Test Perturbative QCD to* $\mathcal{O}(\alpha_s^2)$, Z.Phys.C **43** (1989) 331.

[60] M.Z. Akrawy et al. (OPAL Collaboration), *A Study of Jet Production Rates and a Test of QCD on the* Z^0 *Resonance*, Phys.Lett.B **235** (1990) 389.

[61] T.D. Gottschalk and M.P. Shatz, *A Reassessment of the* $\mathcal{O}(\alpha_s^3)$ *Three Jet Cross-section for* e^+e^- *Annihilation*, Phys. Lett. B **150** (1985).

[62] G. Kramer and B. Lampe, *Jet Cross-Sections in* e$^+$e$^-$ *Annihilation*, DESY-86-119, Fortsch.Phys. 37 (1989) 161.

[63] S. Bethke, Z. Kunszt, D.E. Soper and W.J. Stirling, *New jet cluster algorithms: Next-to-leading order QCD and hadronization corrections*, Nucl.Phys.B **370** (1992) 310-334, Nucl.Phys.B **523** (1998) 681-681 (erratum).

[64] R.D. Field and R.P. Feynman, *A parametrization of the properties of quark jets*, Nucl. Phys, B **136** (1978) 1.

[65] P. Hoyer et al., *Quantum Chromodynamics and Jets in e+e-*, Nucl. Phys. B**161** (1979) 349.

[66] A. Ali et al., *A QCD Analysis of the High-Energy* e$^+$e$^-$ *Data from PETRA*, Phys. Lett. **93B** (1980) 155.

[67] B. Andersson et al., *How to find the gluon jets in* e$^+$e$^-$ *annihilation* Phys.Lett. **94B** (1980) 211.

[68] W. Bartel et al., (JADE) *Experimental study of jets in electron-positron annihilation*, Phys. Lett. B **101** (1981) 129.

[69] W. Bartel et al.(JADE), *Particle Distribution in Three Jet Events Produced by* e$^+$e$^-$ *Annihilation*, Z.Phys.C **21** (1983) 37.

[70] W. Bartel et al. (JADE), *Test of Fragmentation Models by Comparison with three-jet Events produced in* e$^+$e$^-$ $\rightarrow$ *hadrons*, Phys. Lett. B **134** (1984) 275.

[71] H.J. Behrend et al (CELLO), *On the Model Dependence of the Determination of the Strong Coupling Constant in Second Order QCD From* e^+e^- *Annihilation Into Hadrons*, Phys.Lett.B **138** (1984) 311.

[72] M. Althoff et al. (TASSO), *A Study of Three Jet Events in* e^+e^- *Annihilation Into Hadrons at 34.6-GeV Center-Of-Mass Energy*, Z.Phys.C **29** (1985) 29.

[73] H. Aihara et al (TPC Collaboration), *Tests of models for parton fragmentation using three jet events in* e^+e^- *annihiliation at* $\sqrt{s} = 29$ *GeV*, Phys.Rev.Lett. **54** (1985) 270, Phys.Rev.Lett. **54** (1985) 1209 (erratum).

[74] Ya.I. Azimov, Yu.L. Dokshitzer and V.A. Khoze, *The String Effect and QCD Coherence*, Phys. Lett. B **165** (1985) 147.

[75] W. Bartel et al. (JADE), *Experimental evidence for differences in* $\langle p_\perp \rangle$ *between quark jets and gluon jets*, Phys. Lett. B **123** (1983) 460.

[76] W. Bartel et al. (JADE), *Charged Particle and Neutral Kaon Production in* e^+e^- *Annihilation at PETRA*, Z. Phys. C **20** (1983) 187.

[77] Z. Koba, H. Nielsen and P. Olesen, , Nucl. Phys. B **40** (1972) 317.

[78] W. Bartel et al. (JADE), *Baryon Production in* e^+e^- *Annihilation at PETRA*, Phys. Lett. B **104** (1981) 325.

[79] W. Bartel et al. (JADE), *Precise Measurement of Total Cross Sections for the Process* $e^+e^- \to$ *multihadrons in the CM Energy Range Between 12.0 and 36.4 GeV*, Phys. Lett. B **129**145.

[80] W. Bartel et al. (JADE), *A Measurement of the Total Cross Section and a Study of Inclusive Muon Production for the Process* $e^+e^- \to$ *hadrons in the energy range between 39.79 GeV and 46.78 GeV*, Phys. Lett B **160** (1985) 337.

[81] F.A. Berends and R.Kleiss, *Initial State Radiation for* e^+e^- *Annihilation Into Jets*, Nucl. Phys. B **178** (1981) 141.

[82] G. Arnison et al. (UA1 Coollaboration), *Experimental Observation of Lepton Pairs of Invariant Mass Around 95 GeV/c**2 at the CERN SPS Collider*, Phys. Lett. **B126** (1983) 398.

[83] P. Bagnaia et al. (UA2 Collaboration), *Evidence for* $Z^0 \to e^+e^-$ *at the CERN* $p\bar{p}$ *collider*, Phys. Lett. **B129** (1983) 130.

[84] W. Bartel et al., *Observation of a Charge Asymmetry in* $e^+e^- \to \mu^+\mu^-$, Phys.Lett.B **108** (1982) 140.

[85] W. Bartel et al., (JADE), *New results on* $e^+e^- \to \mu^+\mu^-$ *from the JADE detector at PETRA*, Z. Phys. C **26** (1985) 507.

[86] W. Bartel et al. (JADE), *A measurement of the electroweak induced charge asymmetry in* $e^+e^- \to b\bar{b}$, Phys. Lett. B **146** (1984) 437.

[87] W. Bartel et sl. (JADE), *Search for New Flavor Production at PETRA*, Phys. Lett. **B** 89 (1979) 136.

[88] R. Marshall, *The Separation of Quark Flavors in* e^+e^- *Annihilation and Its Applications*, Z. Phys. C **26** (1984) 291.

[89] A.J. Buras, *Photon structure functions: 1978 and 2005*, Acta Phys.Polon.B **37** (2006) 609; hep-ph/0512238.

[90] T.F. Walsh, Peter M. Zerwas, *Two Photon Processes in the Parton*

Model, Phys. Lett. B **44** (1973) 195.

[91] W. Bartel et al. (JADE), *Experimental Study of the Photon Structure Function F_2 at Q^2 from 10 GeV^2 to 220 GeV^2*, Z. Phys. C **24** (1984) 231.

[92] S. Bethke, *Data Preservation in High Energy Physics - why, how and when?*, contribution to: QCD 10, Montpellier 2010, Nucl. Phys. B Proc. Suppl. 207-208 (2010) 156, e-Print: 1009.3763 [hep-ex].

[93] J.E. Olsson, *The Preservation of the JADE Data (and Software)*, presentation given at the JADE revival meeting at DESY, August 2009, https://nextcloud.mpp.mpg.de/nextcloud/index.php/s/ SLBpNDe7eY2SmeL?dir=undefined&path=%2FJADE%20Meetings& openfile=826475.

[94] https://opendata.cern.ch/, 2021.

[95] V. Blobel, *The BOS System*, https://www.desy.de/~sschmitt/blobel/bosman.pdf

[96] V. Blobel, *FPACK manual*, https://www.desy.de/~sschmitt/blobel/fpack.txt

[97] G. Eckerlin and M. Zimmer, *A New Compact Data Format Description of Bank ZE4V*, JADE Computer Note99, 1988.

[98] P.A. Movilla Fernandez, *A guide to the resurrected JADE data and software*, JADE Computer note 103, MPP-2003-279 (2003).

[99] https://cernlib.web.cern.ch/cernlib/.

[100] *High Level Interface to Graphics and Zebra Users Guide*, CERN Program Library Long Writeups Q120 and Y251, https://cds.cern.ch/record/ 2296381/files/higz.pdf (1998).

[101] R. Brun and F. Rademakers, *ROOT - An Object Oriented Data Analysis Framework*, Proceedings AIHENP96 Workshop, Lausanne, Sep. 1996, Nucl. Inst. Meth. in Phys. Res. A 389 (1997) 81-86; see also https:// root.cern.

[102] https://cmake.org

[103] https://github.com.

[104] A. Buckley et al., *The HepMC3 event record library for Monte Carlo event generators*, Comp.Phys.Comm. 260 (2021) 107310, arXiv:1912.08005 [hep-ph].

[105] S. Bethke, *QCD Studies at LEP*, Phys.Rept. 403-404 (2004) 203, hep-ex/0406058.

[106] P.A. Movilla-Fernandez et al., *A Study of event shapes and determinations of α_s using data of* e^+e^- *annihilations at $\sqrt{s}$ = 22 GeV to 44 GeV*, Eur. Phys .J. C **1** (1998) 461, hep-ex/9708034.

[107] P.A. Movilla-Fernandez, *Studien zur Quantenchromodynamik und Messung der starken Kopplungskonstanten α_s bei $\sqrt{s}$ = 14 − 44 GeV mit dem JADE Detektor*, PhD thesis RWTH Aachen, PITHA 03/01 (2003).

[108] S. Kluth et al., *QCD studies with resurrected JADE data*, Contribution to 38th Rencontres de Moriond on QCD and High-Energy Hadronic Interactions, hep-ex/0305023.

[109] P. Pfeifenscheider et al. (JADE and OPAL Collaborations), *QCD analyses and determinations of α_s in e^+e^- annihilation at energies between 35 GeV and 189 GeV*, Eur. Phys. J. C **17** (2000) 19, hep-ex/0001055.

[110] S. Bethke et al. (JADE Collab.), *Determination of the Strong Coupling α_s from hadronic Event Shapes with $\mathcal{O}(\alpha_s^3)$ and resummed QCD predictions using JADE Data*, Eur. Phys. J. C **64** (2009) 351, e-print 0810.1389 [hep-ex].

[111] P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

[112] G. Abbiendi et al. (OPAL Collab.), *Determination of α_s using OPAL hadronic event shapes at $\sqrt{s}$ = 91 - 209 GeV and resummed NNLO calculations*, Eur. Phys. J. **C71** (2011) 1733.

[113] https://www.nobelprize.org/uploads/2018/06/advanced-physicsprize2004.pdf

[114] *Status Report of the DPHEP Study Group: Towards a Global Effort for Sustainable Data Preservation in High Energy Physics*; Z. Akopov et al. (The DPHEP Study Group), e-Print: 1205.4667 [hep-ex];
Data Preservation in High Energy Physics, https://dphep.web.cern.ch.

[115] K. Cranmer et al., *Analysis Preservation and Systematic Reinterpretation within the ATLAS experiment*, J. Phys.: Conf. Ser. 1085 (2018) 042011.