The Road to Discoveries:
The Role of the Max-Planck-Institute for Physics in High Energy Collider Experiments

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1 Introduction

The Max Planck Institute for Physics was founded as *Kaiser-Wilhelm-Institut für Physik* in 1917. In the first years its task was to distribute research resources among the German universities. In 1938 the Institute moved to its first own building in Berlin. From then on the institute conducted it's own research. In 1942 Werner Heisenberg became director at the KWI for Physics. In 1946 the institute was restarted in Göttingen and 1948 it was renmaed to *Max-Planck-Institut für Physik*.

2 Colliders, Detectors, Physics: MPP's Role in the Discovery of New Phenomena

Until the 1930s nature seemed to only have created three *elementary* particles, indispensable for the construction of matter: proton, neutron and electron. The idea of strict economy as a principle of nature was shaken, however, when, in 1948, the π-meson was observed in processes induced by cosmic radiation. The "pion" was the first elementary particle not present in ordinary stable matter.

To study its properties in more detail and in order to become independent from cosmic radiation, new, increasingly powerful particle accelerators were built, while, in parallel, detection methods were developed, which allowed to study particle collision in fine detail. The rapid development of bubble chambers, as an example, permitted to study the properties of particles, like mass, lifetime, spin and magnetic moment with high accuracy.

A milestone in the development of accelerators was the CERN Proton Synchrotron (PS), operating since 1959, able to deliver protons with up to 30 GeV. Many new particles were discovered in subsequent years, forming "families" of baryons and mesons. Some of them had unexpectedly long lifetimes, which was the first hint to the existence of "quarks" as a *substructure* of hadrons. A new type of quark, called "strange", not present in stable matter, was considered as causing the long lifetime of those particles.

The mass scale of newly detected particles seemed to have no obvious upper limit. To open the window for the discovery of ever heavier particles, the Super Proton Synchrotron (SPS) was constructed at CERN, starting 1972, with a maximum energy of 400 GeV. Due to the kinematics of a proton hitting another proton at rest (like in a stationary hydrogen target), an increase of beam energy does not lead to a proportional increase of the energy available for the collision process, because the energy in the Center of Momentum System (CMS) only grows with the square root of the beam energy. If, in contrast, the two particles collided "head-on", the energy in the CMS would be twice the beam energy. This led to the colliding beam concept for High Energy physics experiments, where two beams, circulating in opposite direction, are brought to collide at predefined interaction regions (IA), where, subsequently, the collision products can be observed in detectors surrounding the IA region. In order to explore this concept, a pioneering p-p collider, the Intersecting Storage Rings (ISR) were built at CERN, starting to operate in 1971. The CMS energy was twice the injection energy from the PS, i.e. 60 GeV. Compared to this, the 400 GeV beam energy on proton targets, as produced by the SPS, could only provide a CMS energy of 20 GeV.

Historically, the colliding beam technique was pioneered in collisions between electrons and positrons (e^+ - e^-), because a number of technical aspects helped to facilitate the operation of e^+ - e^- compared to p - p colliders. Pioneering $e^+ e^-$ colliders were built at the Italian National Laboratory for Particle Physics (ADONE), at the Stanford Linear Accelerator Center (SPEAR) and at DESY near Hamburg (DORIS), providing CMS energies of 3, 4 and 8 GeV, respectively. At SPEAR, the J/ψ meson was discovered in 1974 and confirmed at DORIS, which established the existence of the *charmed* quark, partner of the *strange* quark in the second quark generation. A more powerful e^+e^- collider, with an energy of up to 24 GeV per beam (PETRA), was built at DESY, starting to operate in 1978. It was the first collider, where gluons were identified in events with three well-separated hadron jets.

The fact that e^+ and e^- are of opposite charge allows both beams to circulate in the same magnetic field, requiring only one vacuum ring, which leads to an important simplification of the technical implementation. Thus, when anti-proton cooling was invented at CERN in 1976, it appeared that the SPS could be used in the same operation mode, proton and anti-proton being of opposite charge. The SPS was therefore converted into a colliding beam machine, reaching 540 GeV energy in the CMS system, by far the highest energy achieved by that time. It allowed, late in 1983, to prove the existence of the $W^{+/-}$ and Z^0 bosons, which is one of the highlights in the history of CERN.

In the wake of this success, a series of new collider projects was initiated. At CERN, the Large Electron Positron collider (LEP) was built to reach twice 100 GeV and to become a "discovery machine" as well as a "factory" for the production of Z and W bosons. After the termination of the LEP project, anticipated for 2001, the LEP tunnel became free for

Labora-tory	Collider name	Time of operation	Particle types	Beam energies GeV * GeV	Experiment w. MPP involvement
DESY	DORIS	1974 - 2013	$e^+ e^-$	5 * 5	DASP
DESY	PETRA	1978 - 1986	$e^+ e^-$	24 * 24	CELLO (JADE)
CERN	LEP	1989 - 2000	$e^+ e^-$	104 * 104	Aleph (OPAL)
DESY	HERA	1992 - 2007	$e^\pm$ p	30 * 920	H1
BNL	RHIC	2000 - now	p * Ion	255 * 100/n	STAR
KEK	SuperKEKB	2016 - now	$e^+ e^-$	4 * 7	Belle II
CERN	LHC	2008 - now	p p	6800 * 6800	ATLAS

Table 1: Collider projects with substantial MPP participation. For the beam energies the maximally reached values are given. The projects in brackets came to the MPP in 2000 with the new director Prof. Bethke.

a powerful new p - p collider, planned to operate at $2 \times 7\,\text{TeV}$, called the Large Hadron Collider (LHC).

All along the rapid development of particle colliders to ever higher CMS energies, MPP took a leading role in planning, testing and constructing experimental facilities, able to cope with increasing requirements for energy resolution, tracking accuracy, angular acceptance and readout speed. Two big experiments with MPP leadership were constructed and operated at the PETRA and HERA colliders at DESY. Using sampling calorimeters in a Liquid Argon medium (LAr), the detection of neutral particles and hadronic jets was brought to a high level of perfection and reliability. Table 1 gives an overview of major MPP experiments at colliders.

At CERN, MPP was one of the main proponents of the ALEPH experiment at LEP, where the institute contributed two novel technologies for particle tracking. Thus, from the very beginning, MPP took a leading role in design and construction of the Time Projection Chamber (TPC), in particular in the development of the complex structures of the end plate with demanding requirements for mechanical accuracy and reliability of the TPC as well as for the high level of timing accuracy of the readout electronics. MPPs second, crucial contribution to tracking was the Silicon Strip detector, allowing to measure tracks with the unprecedented accuracy of about $10\,\mu$m. This way, secondary vertices could be identified, which were displaced from the beam interaction point by a very short distance, a key feature to identify decays of B-mesons. Based on this capacity, ALEPH became leader in the exploration of B-physics at LEP. The experience gained with the ALEPH TPC was later used in the STAR experiment at the RHIC collider (Relativistic Heavy Ion Collider) at BNL, where MPP contributed a new type of TPC, optimized for the very forward region.

While LEP went into operation at CERN, a special form of collider was constructed at DESY, allowing collisions between protons and electrons at the HERA storage rings. MPP was responsible for calorimetry in the H1 experiment as well as for a new strategy of trigger formation with Neural Networks. The calorimeter at H1, based on LAr technology, achieved the planned energy resolution and demonstrated high reliability during operation.

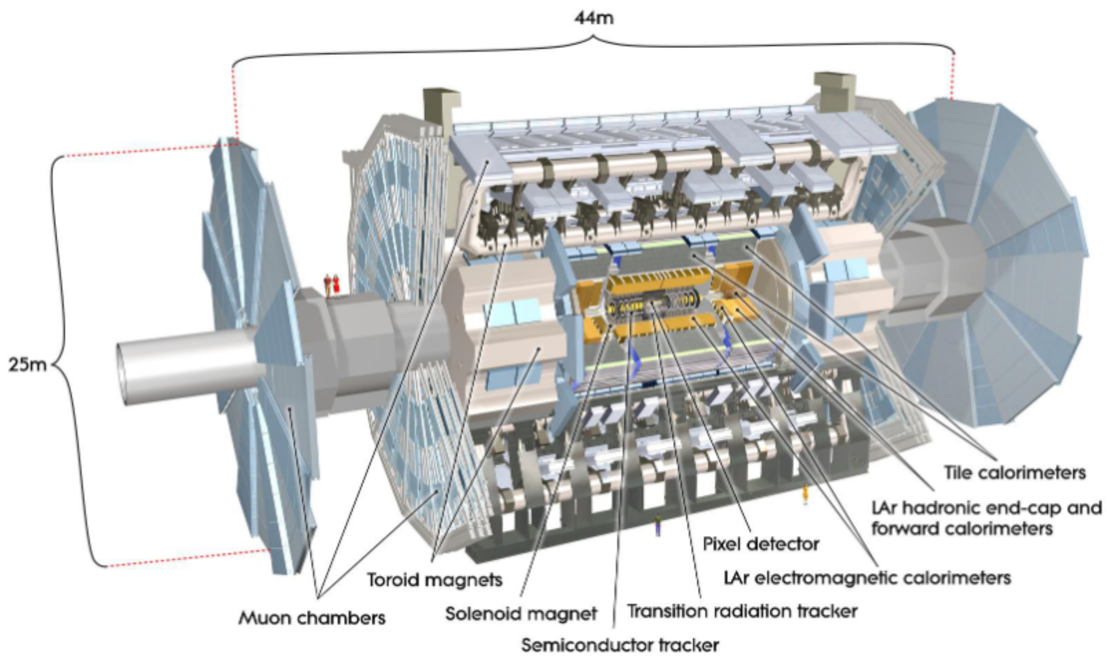

Figure 1: Cutaway view of the ATLAS detector with the central tracking detector (see chapter 2), the calorimeters (see chapter 3), and, surrounding everything else, the central cylindrical (barrel) and the endcap parts of the muon spectrometer with their separate superconducting toroid magnet systems. The precision muon tracking chambers (MDT) constructed at MPP (see chapter 4) are located in the outermost layer of the central cylindrical (barrel) part, mounted on the outside of the eight superconducting barrel toroid magnet coils, as indicated in the picture.

While LEP was in the final phase of construction, CERN vigorously pursued planning and prototyping for the follow-up project LHC. In parallel, on the side of the experimenters, work on detector concepts was taking shape. MPP proposed a detector type with the unique feature of a superconducting magnet with toroidal geometry (ASCOT), which did not use an iron core and – for this reason – was nearly transparent for muon particles emerging from the interaction point. When the ASCOT proposal was finally merged with another project - EAGLE - to become ATLAS, the iron-free magnet design was adopted, because the accuracy of muon tracking was one of the crucial requirements for a potential observation of the Higgs particle.

When the LHC became reality, planning for ATLAS entered a new phase. MPP played a crucial role in defining the technology in three subdetectors:

- The Inner Detector (ID) had to measure particle tracks with high accuracy in a background rate of about 10^9 particles per second. In the innermost region, close to the beam pipe, this could only be done by Silicon Strip detectors, and MPP, based on the experience at LEP, led the development of detectors as well as the design of efficient readout strategies.

- The Endcap calorimeters for the precise measurement of hadronic showers were designed and built by MPP, in collaboration with other institutes.

- The Superconducting Toroidal magnets in the voluminous outer region had to be equipped with muon detectors with very high spatial resolution, covering about $5000\,m^2$. MPP conceived a novel concept for particle tracking, the Monitored Drift Tube technology (MDT), combining high accuracy of tracking and alignment, robustness in operation and cost-effectiveness of production.

At present, the LHC being in its 15th year of operation, the technical concepts developed by MPP have proven to completely match or exceed expectations.

Even before the LHC went into operation (2008), ideas for a luminosity upgrade of the LHC were discussed, which resulted in the construction of the High-Luminosity LHC (HL-LHC). A luminosity increase by an order of magnitude beyond the one of the "original" LHC ($10^{34}\,cm^{-2}\,s^{-1}$) was conceived. An upgrade at this scale, however, meant a big challenge to experimenters, as increased data recording capabilities and higher detector granularity were required for the various subdetectors of ATLAS. Among other technical requirements, a new trigger concept with higher latency was needed as well as a significantly higher bandwidth for data processing and readout, which, in consequence, lead to the necessity of a complete renewal of the readout electronics in all subdetectors. Detector elements, exposed to high particle rates or radiation doses, would have to be replaced by devices with higher hit capability, granularity and radiation tolerance.

As for the muon tracking detectors, drift tube detectors with smaller tube diameter (sMDT) were developed to provide eight times higher rate capability. In a sequence of development steps, a series of constantly improved sMDT chambers was added to the existing ATLAS structure, in such a way as to test the new technology under real experimental conditions. The complete Inner Detector of ATLAS will be replaced by an all-Silicon barrel tracker with finer granularity and higher radiation tolerance. At the time of this article, work for the upgrade to the HL-LHC is in full swing and driven by a fixed production and installation schedule.

The future of highest energy particle colliders beyond the HL-LHC is a matter of intense discussion since a long time and not yet fully clarified. The Future Circular Collider (FCC) project promoted at CERN is a large e^+e^- collider of about 90 km circumference to be used as a "Higgs factory" (FCC-ee), to be followed by a p p collider in the same tunnel with around 100 TeV collision energy. In all scenarios of future colliders, detectors with high granularity, high spatial and energy resolution will be needed, being able to work at high particle rates and high radiation levels. The MPP is well prepared for this scenario, taking advantage of its long-standing experience in detector design, realization and operation.

3 Vertexing: Pioneering Silicon Detectors

3.1 Silicon Detectors in High Energy Physics

The Max Planck Institute for Physics has been playing a leading rôle developing silicon detectors for applications in High Energy Physics. This started in the seventies when the MPP physicists Gerhard Lutz and Robert Klanner, together with Josef Kemmer from the TUM, developed the first useful silicon strip detectors for fixed target experiments.

If precision, compactness, and speed is required silicon is the detector material of choice. In silicon about 3.6 eV of energy loss is needed to create an electron hole pair, the ionization energy in gases is in the order of 15 eV for argon and even higher for other gases. In addition the ionization density is higher: a minimum ionizing particle creates 800,000 electron hole pairs per cm in silicon but only 100 electrons per cm are created in a gas like argon. The signals in silicon can be amplified directly with charge sensitive amplifiers. No high fields for gas amplification are needed. Hence comfortably large signals can be obtained in very thin layers of silicon. Because of this and the possibility to pattern the detectors very finely using photolithography a superior position resolution can be achieved.

Silicon detectors had their first appearance in High Energy Physics in the seventies when high precision vertex detectors were needed for lifetime measurements of the recently discovered charmed particles. Lifetimes in the picosecond range required a spatial resolution of a few $10\,\mu$m in order to resolve the decay vertex from the production vertex. Bubble chambers and emulsions, which could in principle achieve such a resolution, could not cope with large data rates. Gaseous detectors were fast, but not precise enough. Silicon detectors could be segmented fine enough to provide sufficient resolution at the required speed.

However, first a series of technical problems had to be overcome. The breakthrough was the introduction of the planar process by J. Kemmer [1] which made it possible to construct high quality detectors, replacing the surface barrier technology proposed earlier [2]. The ACCMOR collaboration (**A**msterdam, **C**racow, **C**ERN, **M**unich, **O**xford, **R**utherford) operating the NA11 (1978-1982) and NA32 (1982-1986) experiments [3] at CERN were the first to use these silicon strip detectors. The readout electronics was bulky and had to be connected to the detectors using large fan-out boards as shown in Fig. 2. Hence the use of silicon detectors was limited to fixed target experiments with their telescope-like detectors. These experiments made important contributions to the measurement of the lifetimes of charmed Mesons [4] and Baryons [5].

3.1.1 Vertex Detectors at LEP: ALEPH (1989-2000)

In order to use silicon strip sensors in the upcoming LEP experiments with their 4π detectors miniature electronics was needed which could allow a direct coupling of an amplifier to a silicon strip requiring a width of the amplifier of O($100\mu m$). The introduction

Figure 2: Photo of the first silicon strip detector made in planar technology. This detector was used in the NA11/NA32 experiment. The sensor's sensitive area is $24 \times 36\,\mathrm{mm}^2$. The sensor is embedded in a large fan out board providing cable connections to individual amplifiers.

of VLSI (**V**ery **L**arge **S**cale **I**ntegration) electronics made it possible to construct compact silicon detectors which could be installed in colliding beam experiments. One of the first VLSI chips for silicon strip detector readout was the CAMEX64 [6] developed at MPP and the Fraunhofer Institute in Duisburg by Gerhard Lutz for the ALEPH experiment.

MPP was member of the ALEPH collaboration (and played a leading role in the construction of the superb TPC (**T**ime **P**rojection **C**hamber)) and, together with INFN Pisa, constructed the first Vertex detector using double sided silicon strip detectors [7]. Pisa originally proposed a silicon vertex detector using single sided detectors, however. MPP joined the proposal extending it to the use of double sided detectors.

Simple single sided strip sensors measure only one coordinate of a track. This matches the resolution of the outer (gaseous) tracking detectors where high resolution is only needed in the bending plane of the magnetic field. However, the tracks of decaying particles are distributed isotropically in $r - \phi$ and z and a projective measurement results in a loss of information and precision. Measuring two coordinates of a track with rotated strips provides a two-dimensional measurement, improving the possibilities of vertex reconstruction. This can be achieved by rotating the strip directions in different sensor planes resulting in a kind of stereo view. One step further is a real double sided detector: both surfaces of a sensor are instrumented collecting either electrons or holes, again with the strip directions rotated. One disadvantage of such stereo arrangements are association ambiguities in case more than one track traverses the detector. At LEP the track density was low enough so that there was no severe limitation due to these ambiguities. A further complication is the double sided processing required for such detectors. In standard single sided detectors the backside of the silicon wafer needs, besides a homogeneous implant and passivation, no further processing, making the handling during production rather easy. In double sided detectors the back side needs to be patterned as well introducing many complications in the production process. First trials to produce such detectors in the laboratory of Josef Kemmer at MBB delivered prototypes demonstrating that such detectors could work but failed to produce detectors with high production yield and 100% strip efficiency. Finally we found with CSEM in Neuchatel a company able to produce such detectors according to our specifications. ALEPH was the first experiment to use double sided silicon sensors. Other features of the sensors were the punch-through biasing of the p-strips and the use of the electron accumulation layer as bias resistor on the n-side. The detectors were DC-coupled. AC coupling to the amplifier was made using special capacitor ASICs bonded between the strips and the amplifiers. This reflected the initial difficulty to produce AC-coupled sensors with high yield. Separating the AC coupling to an external, cheap and testable AC chip was a cost effective solution despite some complication for module construction. Another problem was the placement of the readout ASICs for the strips measuring the z-coordinate (along the beam). ALEPH placed them along the detector which resulted in an increase of material. Nevertheless the total amount of material of the two layer detector was only $3\%\,X_0$ (average) for orthogonal tracks.

Altogether the way to go was long and difficult and not without tensions between the Pisa and MPP groups. Many components had to be designed basically from scratch without prior experience, like lightweight but rigid mechanical structures, fine pitch ceramic hybrids. We also had to learn how to do fine pitch wire bonding. The original design foresaw the detector to be fixed on the beam pipe, therefore being the first subdetector to be installed. Delays in construction and schedule constraints made this very soon impossible. Instead we developed a method to install the mini vertex later by use of a kind of ropeway which allowed to drag the detector in its position, defined be rails, from the outside. In 1989 a first prototype was installed consisting only of three modules. It performed very badly suffering from huge common mode noise caused by beam pick up which could not be compensated. In 1990 a new vertex detector was installed in ALEPH (Fig. 3). Despite various improvement it still showed poor performance, however could be tuned to deliver useful data. Unfortunately the detector was partially destroyed by a beam accident. We started to construct a new detector essentially from scratch to be ready in 1991. In the meantime LEP proposed to replace the rather large beam pipe of LEP (radius: 7.8 cm), which resulted in a large extrapolation error, by a smaller one. The radius was reduced to 5.3 cm and the new vertex detector could be placed closer to the beam.

This detector had two layers at radii of 6.3 cam and 10.9 cm and achieved a position resolution of 12μ. The vertex detector proved to be an indispensable part of the ALEPH detector systems, contributing to many measurements. Among them were precise measurements of the inclusive lifetime of B-hadrons [8], the individual lifetimes of B^0, B^+, B_s mesons and b-baryons [9, 10, 11]. The first direct measurement of $B^0\overline{B}^0$-oscillation frequency was performed by ALEPH [12]. The Mini vertex was the decisive detector for the precision measurement of the branching fraction $Z \rightarrow b\bar{b}$: Using impact parameter tagging it was possible to select pure samples of B-events with high efficiency [13]. A nice example of the power of the vertex detector is a fully reconstructed B_s^0 decay observed in the ALEPH detector (Fig. 4). The secondary and tertiary vertices of the $B_s \rightarrow D_s\pi$ decay chain are nicely resolved. This illustrates how B-mesons can be reconstructed and lifetimes measured. Such fully reconstructed events are rare, ALEPH reconstructed only one in 11×10^6 Z events, therefore mostly partially reconstructed events are used in the analysis, e.g. with neutral particles missing.

ALEPH and DELPHI had silicon strip detectors right from the beginning. The other two LEP experiments, OPAL and L3 joined the silicon club later.

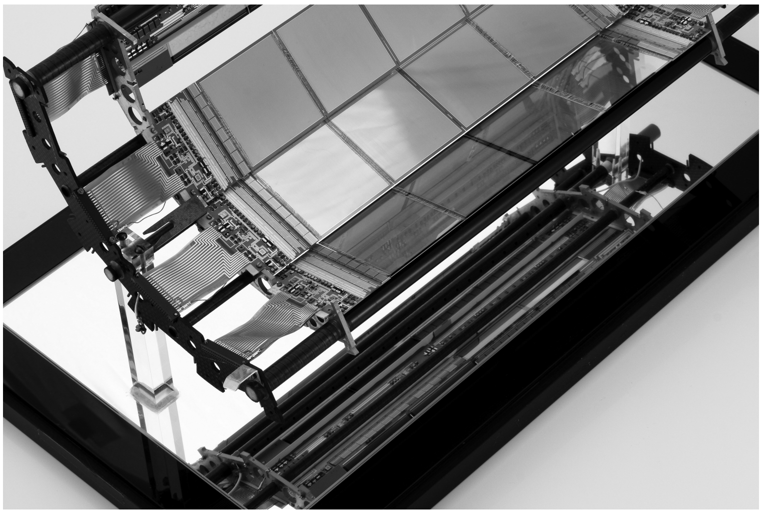

Figure 3: Photo of a sector of the first ALEPH silicon vertex detector. The detector was divided in three sectors, each housing two layers of four modules each. Three of the inner layer modules are shown, one is removed to show the z-side of a module of the second layer. This detector was the first using double sided silicon strip sensors and was used in the 1990 ALEPH run. It was replaced 1991 by a new detector with smaller inner radius. The dimensions of the silicon sensors are $52 \times 52\,\mathrm{mm}^2$.

3.2 The Semiconductor Laboratory: HLL

After the experience with ALEPH it became evident that the optimal development and production of high quality silicon detectors needs a special, dedicated laboratory with production facilities. While collaboration with industry is in principle possible, it introduce severe boundary conditions which hamper innovation. Industrial processes are usually optimized for low cost mass production. Special processing needed for our detectors are either not available or the company is reluctant to adopt the process parameters to our needs. Often these parameters are not disclosed which makes it very difficult to optimize the design of the detectors. Fortunately, our colleagues form the Max Planck Institute for Extraterrestrial Physics faced the same problem developing silicon detectors for X-ray imaging. Both institutes joined to found a common semiconductor laboratory (**H**alb**l**eiter**l**abor: HLL) in 1990.

The lab was located in Pasing, in rooms used by the Fraunhofer Institut für Festkörpertechnologie before. It included 250 m^2 of a class 10-100 cleanroom equipped for processing of 4 inch wafers. This was completed by test facilities and office space for design, analysis and

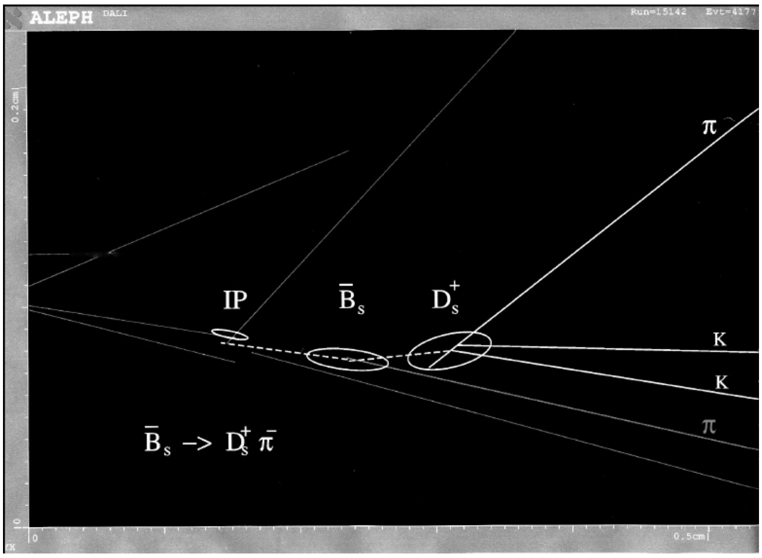

Figure 4: A $\bar{\mathrm{B}}_\mathrm{s}$ decaying into a $\mathrm{D}_\mathrm{s}^+\pi^-$ with the subsequent decay of the D_s^+ into a π^+ and two oppositly charged Kaons fully reconstructed in the ALEPH detector. The error ellipses (3σ) of the interaction point (IP) and two decay vertices are indicated. All tracks are extrapolation of tracks measure in the vertex detector. The $\bar{\mathrm{B}}_\mathrm{s}$ decayed after 1.57 mm, the D_s^+ at 2.71 mm from the IP.

administration. The lab was very successful, the pn-CCDs for the XMM-Newton satellite were fabricated there. However, many applications demanded large detectors which would not fit on a 4-inch wafer. In addition environmental constraints motivated a move of the lab to Neuperlach. There we found perfect conditions on the Siemens Campus: 1000 m^2 cleanroom, with 600 m^2 of class 1 (Fig. 5).

In addition the lab profited from the production facilities of Siemens supporting the maintenance of our cleanrooms and offering services like ion implantation and waste water processing. The lab was now equipped for 6 inch wafers which allowed to engage in the development of detectors for ATLAS SCT, ILC, Belle II and other projects. A strength of the lab were 3D-simulations of silicon detectors which allowed us to design the electric fields in the silicon bulk, optimizing drift and charge collection properties. The laboratory got also more and more involved in the development and fabrication of sensors for other institutes of the Max-Planck-Society. This was one reason that the organisation of the laboratory was changed in 2013. It became an independent entity of the Max-Planck-Society. Still it maintains close connections to the MPP.

3.3 Silicon Tracker: ATLAS

Originally silicon detectors were exclusively used for vertexing where it is sufficient to measure the track direction close to the interaction point. Therefore these detectors can be small and need only few silicon sensors. This is different for tracking detectors where

Figure 5: Part of the class 1 cleanroom of the HLL in Neuperlach (2000 -2024)

good momentum resolution requires a long lever arm and several measurements along the track trajectory. Consequently these detector need to be large which excluded silicon detectors for cost reasons. However, in high rate environments, like at the LHC, gaseous detectors cannot be used because of occupancy and radiation damage. Silicon detectors, however, can still be operated under such conditions. Fortunately, the superior resolution of silicon detectors makes allows to achieve the same momentum resolution with a more compact device, leading to an overall reduction of the detector system (magnetic coil, calorimeters) with considerable cost savings balancing in part the higher costs of a silicon tracker. ATLAS [39] is a detector which has to operate in this extremely harsh radiation environment. This introduces new challenges which were unknown at the experiments preformed so far. The intense radiation will change the effective doping of the silicon sensors beyond type inversion, hence provisions have to be made that the sensors still operate with reasonable performance. Cost considerations lead to the choice of rather standard single sided strip sensors with p-strips in n-type bulk [14]. In order to reach full charge collection efficiency after 10^{13} neutrons/cm^2 these sensors need to be biased with voltages of 400V. Multiple guardrings and other layout features ensure stable operation at this high voltage. The sensors have to be cooled ($< -7^o$C) for two reasons:

- Reverse annealing which would eventually increase the depletion voltage beyond 400 V is reduced at that low temperature.
- High leakage currents together with the high operation voltage could lead to self-heating of the sensors which by positive feedback can result in thermal runaway. By cooling leakage currents must be kept below a critical value.

ATLAS SCT uses binary readout. The readout chip has a programmable threshold, only

hits passing this threshold are read out. This simplifies the readout system and reduces the bandwidth. The noise of the system is about 1500 electrons (ENC). With this noise the threshold can be set to achieve a noise occupancy of 10^{-5} at a hit efficiency exceeding 95%. The ASIC is produced in a radiation hard DMILL BiCMOS process [15]. The sensors [14] are single sided, two of them are joined together with the strips along the z-direction connected. Another such pair is positioned back to back with 40 mrad angle to achieve stereo information. The electronic hybrid is either attached to the module end (endcap modules) or bridged across the sensors (barrel modules). These modules are arranged in four barrels (1.5 m long at radii of 28 cm, 36 cm, 43 cm, and 50 cm) and two times nine discs in the forward regions, extending up to $z = \pm 2.7$ m. The complete detector consists out of almost 20000 silicon sensors. The 10000 sensors in the barrel region are rectangular. Three differently shaped wedge type sensors are used in the forward discs. The total area covered is $60\,\mathrm{m}^2$ with 7×10^6 readout channels. This should be compared to the ALEPH detector which had 96 detectors, $0.25\,\mathrm{m}^2$ with 70.000 readout channels.
As mentioned above the low temperature operation requires an efficient cooling system which should still have low mass. ATLAS uses evaporative cooling: liquid C_3F_8 is evaporated in the cooling pipes situated in the module support structure. The temperature is regulated by setting the pressure in these pipes. The heat transport from the sensors and electronics to the cooling contact is made using materials with very high thermal conductivity like carbon-carbon and thermal pyrolytic graphite. To avoid heating of the sensors by the electronics the heat path of both is separated as much as possible. The system is able to remove about 50 kW of power keeping the senors at a temperature of -7^oC.

The specifications of the ATLAS strip detector is shown in Table **??** .

Figure 6: A module of the ATLAS SCT forward disks

MPP was heavily involved in the design and construction of the forward disks. The mechanical desing of the modules and the use and optimization of the heat spreaders made from pyrolitic graphite was done in the technical department. The HLL played a leading role in the design of the silicon sensors, proposing the use of n-in-n detectors. Clearly the capacity of the HLL was not sufficient to produce the large amount of sensors needed for the SCT. However, the production of prototype test sensors allowed to test various design options before the final design was chosen. MPP proposed a novel way of biasing the detectors using implanted resistors instead of the conventional polysilicon resistors.

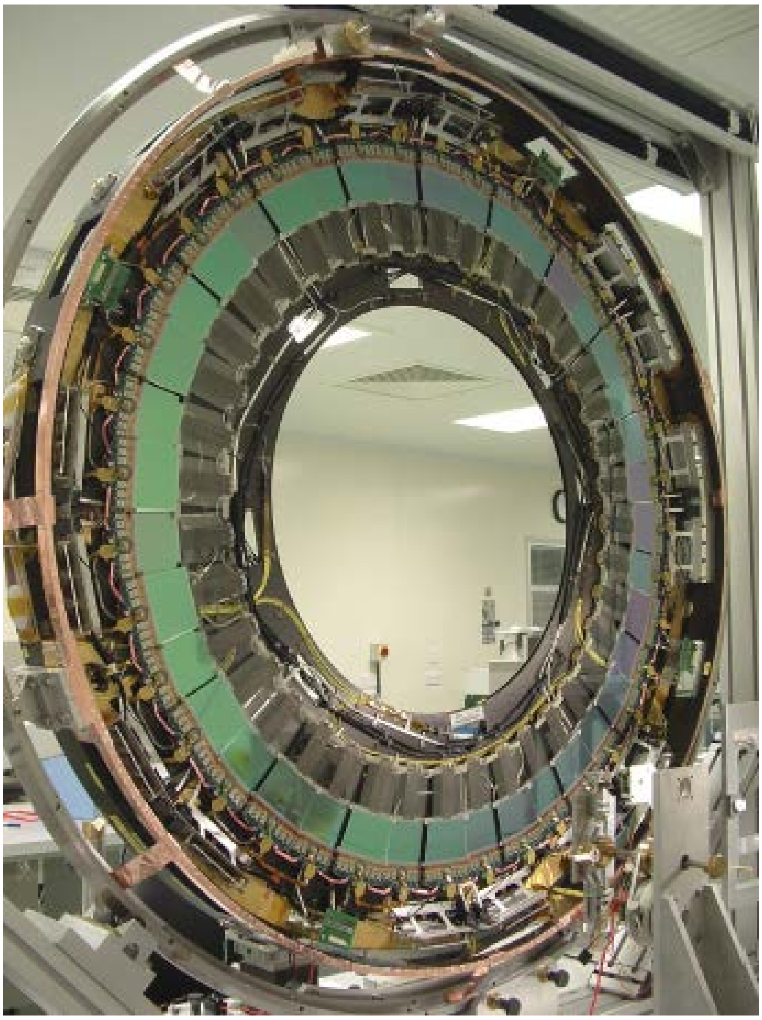

Figure 7: One of the ATLAS SCT forward disk with short middle modules assembled at MPP.

This simplified the production process and reduced the costs, not unimportant for the large scale production required. With CIS in Erfurt MPP found a company which could fabricate the detectors according to our specifications. A fraction of t the detectors for the forward discs were fabricated by CIS, shipped to the HLL and tested there. The second manufacturer was Hamamatsu producing detectors with similar specifications. Then the detectors were distributed to the various assembly sites where the SCT modules were assembled. MPP itself assembled 420 modules for the inner forward rings. Figure 6 shows a forward module produced at MPP and Fig. 7 one of the forward rings equipped with such modules.

The detector started operation in 2011 and is still performing as specified.

Anything about ATLAS pixel? Even more challenging is the innermost region of the ATLAS detector where the pixel vertex detector is located. Especially after the high luminosity upgrade of LHC the radiation damage becomes so severe that standard detectors cannot work anymore. New concepts had to be developed, like thinned n-in-n detectors. Here the MPP contributed together with the HLL to the development of such detectors.

3.4 DEPFET Pixel Detectors: Belle II

At extremely high luminosities the track densities and therefore the detector occupancies in double sided (or any projective) silicon detectors become to large and the ambiguities cannot be resolved any more. Here pixel detectors are needed. A simple diode array detector is rather easy to produce, but the difficulty lies in the readout of thousands of individual pixel. ASIC chips can do the job, but they have to be directly mounted on top of the silicon sensor, besides the challenging small pitch connection technology which introduces a challenge the amount of material per sensors the material budget increases considerably. This is a minor problem for LHC detectors like ATLAS: the particles have high momenta with low multiple scattering. However, if tracks of lower momenta (in the GeV/c regime) need to be reconstructed with high precision very thin detectors are needed and the hybrid concept with the detector-readout sandwich concept fails.

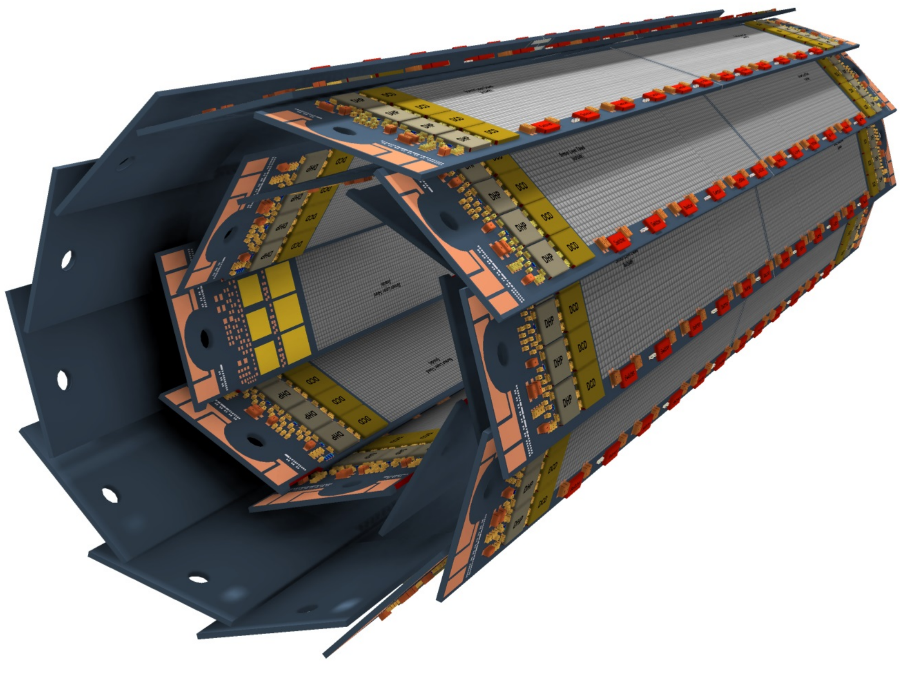

Figure 8: Artist's view of the ladder arrangement of the Belle II PXD. Two modules are glued to form ladders which are arranged cylindrically around the beam pipe in two layers at radii of 1.4 cm and 2.2 cm, the length is 17 cm.

At the HLL we developed a concept of a monolithic silicon pixel detector with an integrated first amplification stage. The amplified signal can then be routed to the readout electronics outside the sensitive area of the device using a rolling shutter scheme. This detector, called

DEPFET (**De**pleted **p**-channel **F**ield **E**ffect **T**ransistor) [16, 17] was originally developed for an experiment at the future ILC collider, but found its first application in the Belle II experiment. Belle II is an upgrade of the original Belle experiment (1999-2010), intended to operate at a 40 times higher instantaneous luminosity. This high luminosity drastically increases the occupancy which makes it impossible to use double sided silicon detectors, as in Belle, for the inner layers of the vertex detector. This was a real problem since precise vertexing is absolutely necessary for the measurement of CP-violation, one of the main motivations of Belle II. The DEPFET detectors which, due to their high signal to noise ratio, can be produced with a sensor thickness as low as $50\mu m$, using a novel technology based on wafer bonding (in the final detector a more conservative $75\mu m$ were used to have a higher S/N allowing to compensate radiation damage). The detector, shown in Figures 8 and 9 consists of two layers with DEPFET modules.

Because of the all-silicon concept (no extra material as carrier needed) and the possibility to place most of the electronics outside the acceptance a material length of only 0.21% X_0 per layer could be achieved. The detector can be compared with a CMOS camera of 6 megapixel producing 50.000 images a second. No other detector concept available at that time (2008) was able to achieve this. When we proposed this to the Belle II collaboration this was immediately accepted and MPP became member of Belle II. This project was exactly the kind of project the HLL was made for: a high performance detector with a novel, sophisticated technology which cannot be produced by industrial partners but still small enough not to exceed the production capacity of the HLL.

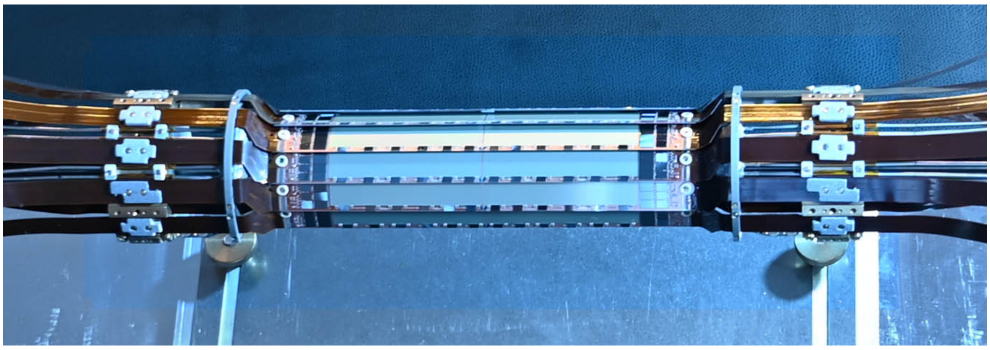

Figure 9: The Belle II PXD after assembly at MPP. The detector has 8 detector elements in the inner layer and 12 in the outer (here visible).

It took a long time to construct the detector, especially the handling of the ultra thin and therefore fragile sensors posed many challenges. Despite all difficulties we managed to install a first version of the detector (with only one of the originally foreseen two layers) right in time for the first physics run in 2019.

With the luminosity collected until 2022 many physics analyses were done demonstrating the excellent performance of this detector. As expected the vertex resolution improved by a factor of two compared to the predecessors Belle and BaBar, as shown in Fig. 10. Notable are the most precise measurements of the lifetimes of D-Mesons [18, 19] and Baryons [20, 21], with a precision improved by a factor of 200 compared to the ACCMOR

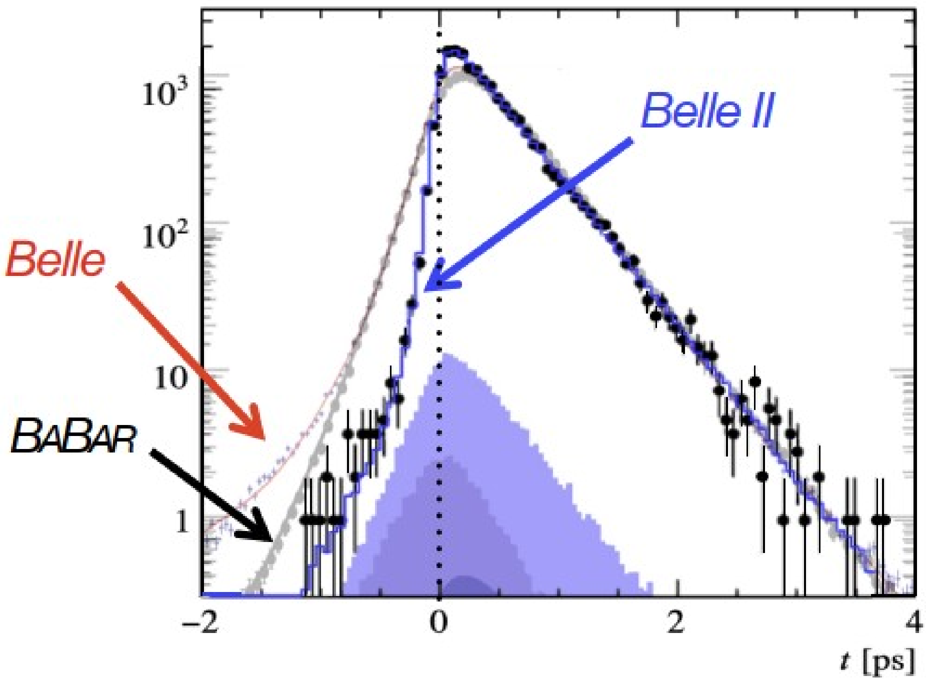

Figure 10: Decay times of D^0-Mesons: the negative tail is a measure of the lifetime resolution which is about a factor of two better at Belle II compared to Belle and BaBar.

measurements four decades earlier. In the shutdown from 2022-2023 a new detector with the second layer completed, was installed and is taking data now. Even today it is still the thinnest vertex detector in a running experiment.

Apart from the unique pixel vertex detector PXD the Belle II detector houses another unique system, also concerned with charged particles, namely a track trigger at the deadtime-free first level, which is based on neural networks. In Belle II two main trigger systems are installed, namely the calorimeter trigger, derived from the electromagnetic Cs(Tl) calorimeter, and the track trigger, using the sense wires from the Central Drift Chamber (CDC). The standard track trigger of Belle II was designed to find tracks in the plane transverse to the beam direction ("2D tracks"), using only the axial wires of the CDC. A major problem for this track trigger are charged particles originating along the beam ("z") direction far from the interaction point (IP) of the colliding electron and positron beams.

It was recognized early by the Belle II group at the Institute that a track trigger needs to be developed which could recognize and reject the dominating rate from the off-Z interactions. While traditional track fits at the first trigger level would exceed by far the allowed latency, the massively parallel computation power of neural networks and their ability to adapt to changing background conditions were chosen to provide a robust first level "z"trigger. The networks use as input the results from the standard Belle II 2D trigger and add the stereo wire information to provide estimates for the origin of the 2D track candidates in direction of the colliding beams ("z-vertex"), as well as their polar emission angles θ. Given the z-vertices of the "neural" tracks allows suppressing the overwhelming background from outside by a suitable cut d. Requiring $|z| < d$ for at least one neural track in an event with two or more 2D input candidates will set an L1 track trigger. The networks also enable a minimum bias trigger, requiring a single 2D track candidate validated by a neural track with a suitable momentum cut in addition to the $|z|$ condition. Both the preprocessing of the input varaibles and the neural computations are implemented on FPGAs with a latency of only 300 ns [22]. The neural trigger is successfully running in Belle II since the year 2020 and has fully replaced the standard 2D track trigger of Belle II.

The hardware level neural network track trigger of the Belle II experiment represents a significant step towards fast and intelligent data collection and processing methodologies in scientific research. The innovative approach to integrate machine learning techniques into the hardware of the experiment indicates the possibility for a paradigm shift towards embracing smarter and faster solutions for real-time event selection. It also sets a precedent for future experiments where efficient and accurate data collection as well as extraction of novel features are essential.

4 Calorimetry in High Energy Physics

In high energy physics experiments calorimetry is a standard procedure to measure the total energy of particles. Particles impacting the calorimeter detector lose via secondary interactions with the absorber material all their energy. Here sampling calorimeters have alternating layers of passive absorber material and active layers, where the deposited energy is measured. When a secondary charged particle passes the liquid argon (LAr) gap. it takes about 23.6 eV to ionize an electron. Applying high voltage at the electrode of the gap, electrons (fast) and ions (slow) drift to the anode resp. cathode. This signal is amplified and recorded and the total integral of these signals is proportional to the impacting particle energy E. With increasing energy the precision of this measurement is increasing and therefore calorimetry is gaining more and more importance at high energies. With rising particle energies E the energy resolution is improving as $\sim 1/E^{1/2}$. Calorimeters are sensitive to charged as well as to neutral particles and the depth of a calorimeter required to absorb all the energy is increasing only logarithmically with energy. Optimizing the lateral segmentation the impact angle of a particle can be measured precisely. The longitudinal segmentation allows to study the shower shape of the impacting particle and thus enables an effective particle identification. A fine segmentation - laterally as well as longitudinally - is crucial when combining track measurements with clusters reconstructed in the calorimeter. Calorimeters are fast detectors and are thus well matched to high luminosity colliders. As quarks fragment into many particles, the jet energy measured at high energies can be directly correlated with the parton energy. With a fine segmented preshower layer an energy correction for inactive material in front of the calorimeter can be obtained, as well as an effective γ /π° separation. These features yield strong arguments for calorimetry at high energy colliders and make the calorimeter an essential part of the detector. In the case of liquid argon calorimeters, where the active layer is a liquid argon gap sandwiched between high voltage electrodes, additional arguments like radiation hardness and signal stability play a key role.

4.1 CELLO - Start of the Liquid Argon Calorimetry at the Institute

The CELLO experiment [23] at the e^+e^- storage ring at DESY with the spokesperson H. Oberlack started 1979. Mainly French and German institutions joined in a combined effort to study e^+e^- interactions at 34 GeV, later increasing up to 47 GeV center of mass energy. The main focus at PETRA was the search for the - at that time - unknown top quark, τ - decays and QCD studies (α_s measurement). Jet studies were thus at the 'gluon discovery machine' an important issue. These goals defined the requirements for the calorimetry at CELLO: very good energy resolution for electrons and photons, good electron/hadron separation, good jet reconstruction and muon identification. The excellent π°, γ and jet reconstruction of the calorimeter were the basis for the success.

The liquid argon calorimeter (LAr) was the optimal choice for the requirements of the e^+e^- physics at PETRA.

The long term stability of the calibration is minimizing any systematics. This holds even for a very harsh environment situation. A high flexibility with respect to lateral and longitudinal segmentation is an important feature. It offers the chance for an optimization of the energy and spatial resolution as well as an effective electron/hadron resp. hadron/muon separation. With a fine segmented preshower layer an energy correction for inactive material in front of the calorimeter can be obtained, as well as an effective γ /π° separation. The Fig.11 shows the schematic view of the CELLO detector. The responsibilities for the Pb/LAr calorimeter were the institute (barrel) and Orsay (endcap), for the tracking detector the institute (drift chamber) and Orsay (proportional chamber) and for the muon chambers Saclay. One of the outstanding features was the thin coil (0.49 $X_\circ$) of the superconducting magnet (1.3 T), thus minimizing any energy losses in front of the calorimeter. The total number of the calorimeter read-out channels was 6880, the total weight of the detector was 1400 t. The calorimeter group of the institute was responsible for the construction of the 2×8 barrel modules, the barrel cryostat with all 16 feed-through's, the read-out electronics, the calorimeter trigger, the data acquisition and the reconstruction software. Pb-strips of 1.2 mm thickness and 2.3 cm width with 3 orientations and 3.6 mm thick LAr gaps were the basic structure. The total thickness of one module was 20 $X_\circ$ with a 6-fold sampling in depth.

Obviously the start of such a project was very challenging for the institute, in particular also for the technical department. The know-how of cryogenic systems had to be developed in house - in collaboration with the Kernforschungszentrum Karlsruhe, with major requirements on quality control. It was a major challenge to get all seals (cover and feed-through's) tight in the cold in view of the mechanical strains and stresses due to the load and temperature gradients. Because of lacking funds, in the first phase the number of read-out channels was reduced with a special cabling scheme. Therefore a reopening of the cryostat with finalizing the originally planned read-out granularity was required. In

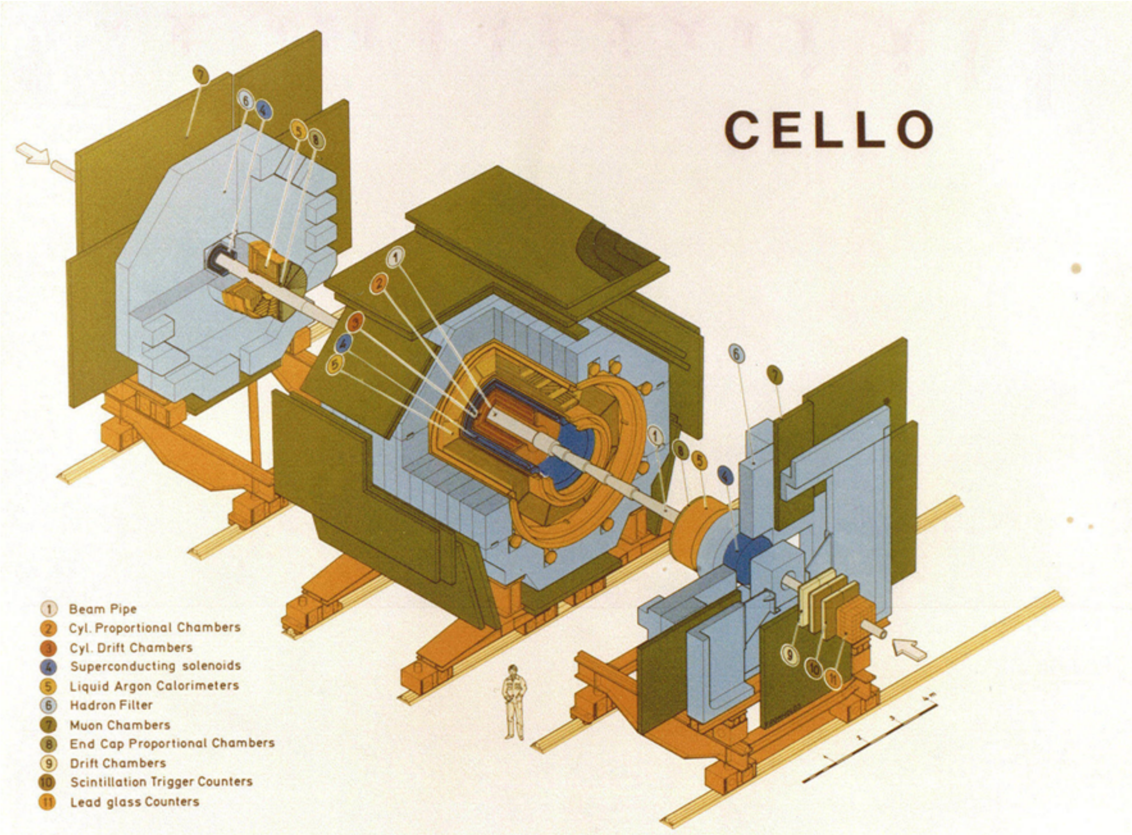

Figure 11: Schematic view of the CELLO detector. Shown are the main detector components: the drift and the proportional chambers of the tracker(2,3), the superconducting magnet(4), the Pb-LAr calorimeter(5), the hadron filter(6) to stop all particles except the muons, and the muon chambers(7).

consequence, welding the cover of the cryostat, as usually done nowadays, was not a valid option. Finally a coil spring coated with PTFE was the optimal solution rather than the usual Indium sealing technique used at that time. Just to give an example, prior to the shipment to DESY the final cryostat has been cold tested in a special construction hall nearby rented by the institute. Also the module construction has been studied in special $R\&D$ tests at CERN to verify the performance for electrons: $\sigma/E = 8.5\%/E^{1/2}$ for the energy resolution and typically 4 mrad for the angular resolution. Finally the Fig.12 shows the insertion of one barrel module in the cryostat of the CELLO detector at DESY.

At PETRA detailed studies of the gluon - with the typical three jet structure in hadronic events - was one of the primary goals. In consequence, high precision α_s determination was a challenging goal for all PETRA experiments. CELLO focused in particular on the systematic issues of the various methods used, as analysis based on thrust, jet masses, energy-energy correlations or total cross section [38].

Among the many physics highlights of the CELLO experiment, one particular analysis should be mentioned here, which took full advantage of the high granularity of its LAr

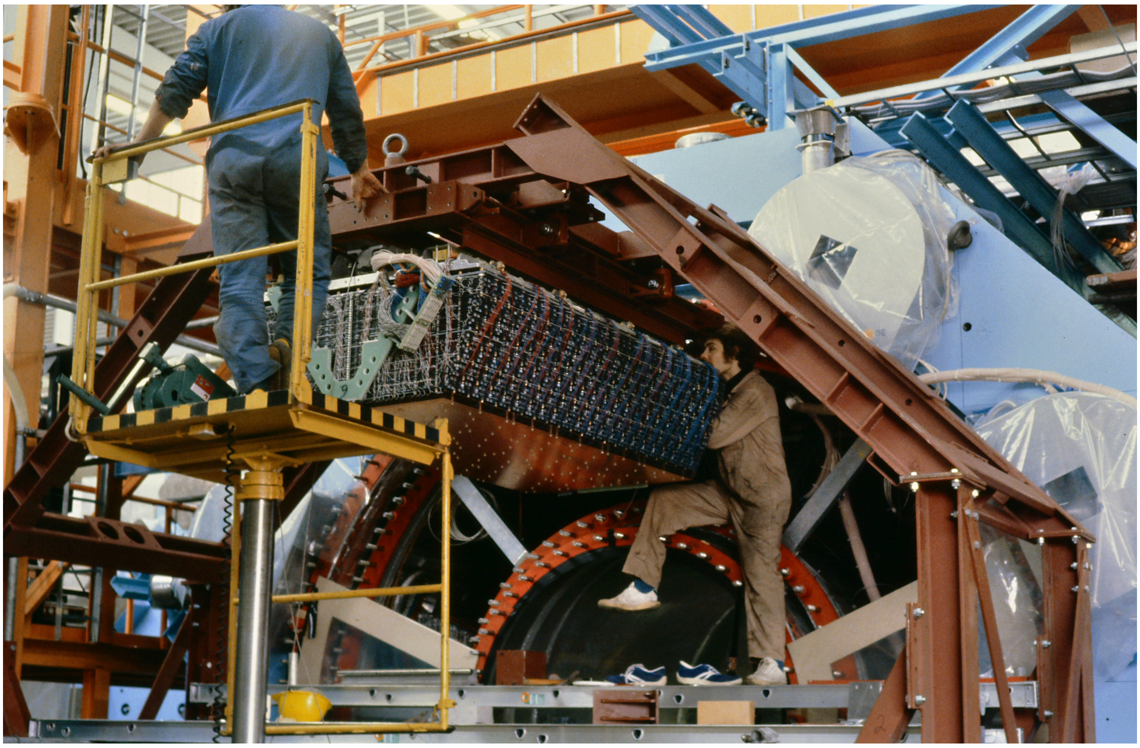

Figure 12: Insertion of one barrel calorimeter module in the cryostat of the CELLO detector at DESY.

calorimeter. With the Cello calorimeter it was possible to solve a long-standing puzzle in the decay branching ratios of the tau lepton. The puzzle was coined as the "1-Prong Problem": The branching ratio of the tau leptons decaying into 1 charged particles plus neutrals (neutrinos and neutral hadrons) was found too small relative to the branching ratio into 3 charged particles plus neutrals. Using the new and highly efficient LAr calorimeter the "missing" neutral particles to contribute to the 1-prong decays were identified as neutral pions, decaying into two photons. A new analysis method using a transition matrix technique finally established the tau lepton with branching ratios and other properties as expected by the Standard Model [24]. The results of the CELLO experiment was later verified by the experiments at LEP, notably by ALEPH.

4.2 H1 - Hadronic Calorimetry and Software Compensation

In 1986 the H1 collaboration started with the construction of the detector (see Fig.13) [25] at the electron proton collider HERA at DESY. The highly asymmetric energies of the electron (27.5 GeV) and proton (820 - 920 GeV) asked for an asymmetric detector [25] - and calorimeter [26] - with special emphasis on the high energy forward (proton) region. The size of the detector was $12 \times 15 \times 10\ m$, the total weight 2800 t. The total number of calorimeter read-out channels was 44352. The study of the proton structure functions, i.e. quark and gluon parton distributions, was one of the primary goals. This is an essential input in pp physics to understand the basic standard model cross sections and thus be able to pin down any deviations pointing to new physics beyond the standard model. The phase space covered for the study of proton structure functions had to be as large as possible. Together with the study of neutral (γ,Z exchange) and charged (W exchange) electroweak currents this yields severe constraints on the calorimeter performance. This holds also for the QCD studies and α_s determination.

The H1 LAr calorimeter (2.4 mm argon gap, see Fig.14) is positioned within a superconducting solenoid to minimize any inactive material in front of the calorimeter.

To match the physics requirements a special optimization of the cracks between the individual modules was necessary (see Fig.15): for neutral current events, where the electron has to be reconstructed with high precision, pointing ϕ cracks have been chosen. The losses are minimized and excluding the bad crack regions the reconstruction is optimal. For charged current events the missing energy has to be reconstructed well, eliminating the option of fiducial volume cuts. Therefore the hadronic calorimeter is designed with non-pointing ϕ cracks, eventhough the worsening of energy reconstruction in a larger acceptance region is the consequence.

The absorber material of the electromagnetic calorimeter is Pb with a thickness of 2.4 mm, sandwiched between two thin fiberglass plates glued to them. The institute was responsible for the forward hadronic calorimeter (FB1, FB2, OF1,OF2) wheels (see Fig.14). The hadronic calorimeter is made of stainless steel (thickness 16 mm) as absorber. The tolerances on thickness and flatness for plates of this size do not allow to define the LAr gap with the required precision. Therefore high precision read-out cells are inserted between the absorber plates. Two outer stainless steel plates define the independent read-out board with a LAr double gap and a G10 read-out structure board in the center. Polyimid films are glued to the stainless steel plates and covered with a high resistive coating for the HV distribution. Thus an effective spatial resolution is obtained without the need for a fine HV pad structure connected via large resistors to HV. In addition, this technique guarantees an optimal HV protection for the read-out amplifiers. Because polyimid films with high resistive coating were at that time not available, the printing of this high resistive layer has been developed in the institute. With the strong requirements on components, drying and bake-out time the printing procedure was done in house. The company in charge did the printing with the quality control by local staff. In a rather unconvential way, the printing machine was given to the company at the end of the construction as part of the payment. Only thus the required precision of a touchy production step could have been guaranteed.

As the steel-LAr calorimeter is non-compensating, a special signal weighting approach has been developed in close collaboration with DESY: the software-compensation. Signals are calibrated according to the signal density which distinguishes hadronic from electromagnetic showers. Detailed beam tests were done at CERN to optimize the detector granularity for this weighting approach, as well as to test the module performance and quality. Finally for different impact angles the calorimeter has been calibrated in dedicated beam runs at CERN. The physics requirements of an energy resolution for electrons of $\sigma/E = 12\%/E^{1/2}$ and for the hadrons (with weighting) of $\sigma/E = 45\%/E^{1/2} \oplus 1\%$ have been achieved.

The H1 LAr calorimeter was also equipped with a very efficient and low-energy threshold trigger at the first level, based on special electronics designed and buit by the Institute's electronics department. As a key feature the LAr trigger was finding individual isolated clusters over almost 4π acceptance. The clusters had a transverse dimension of approximately the size of typical jets at HERA energies, therefore named "Jet Trigger". Each cluster yielded the deposited energy and its polar and azimuth emission angles. With the Jet Trigger, in combination with the track information from the central drift chamber it was, for example, possible to measure the longitudinal structure function of the proton in a completely new kinematic regime [27]. Another highlight from the H1 experiment was the first realization in a HEP experiment of a neural network trigger, trained with real data for specifically selected final states. The basic unit of the neural trigger was a commercial neuromorphic chip integrated on a VME board. This hardware was still pretty slow compared to modern FPGAs, with an execution time of 20 μs. It was therefore deployed on the second trigger level ("L2") of the 4-level H1 trigger system. The neural trigger used the information from the main subdetectors of H1, combine them and do a pattern recognition of physically interesting final states. For an efficient triggering of the desired final states, the conditions of the respective L1 triggers were relaxed and the extra L1 trigger rate, caused by other "background" physics channels, was reduced by the networks to an acceptable level [28].

One of the physical highlight of the neural trigger was the measurement of the cross section for exclusive elastic production of J/ψ mesons as function of the total photon-proton center of mass energy. The H1 result [29] showed a strong increase of the cross section towards large center of mass energies. This result was in disagreement with Regge theory, postulating Pomeron exchange with an almost energy-independent cross section. Later, new predictions based on QCD calculations were found to be in agreement with the H1 measurement.

The Fig.16 shows the first hadronic calorimeter module built in the institute with the H1 calorimeter project leader H. Oberlack.

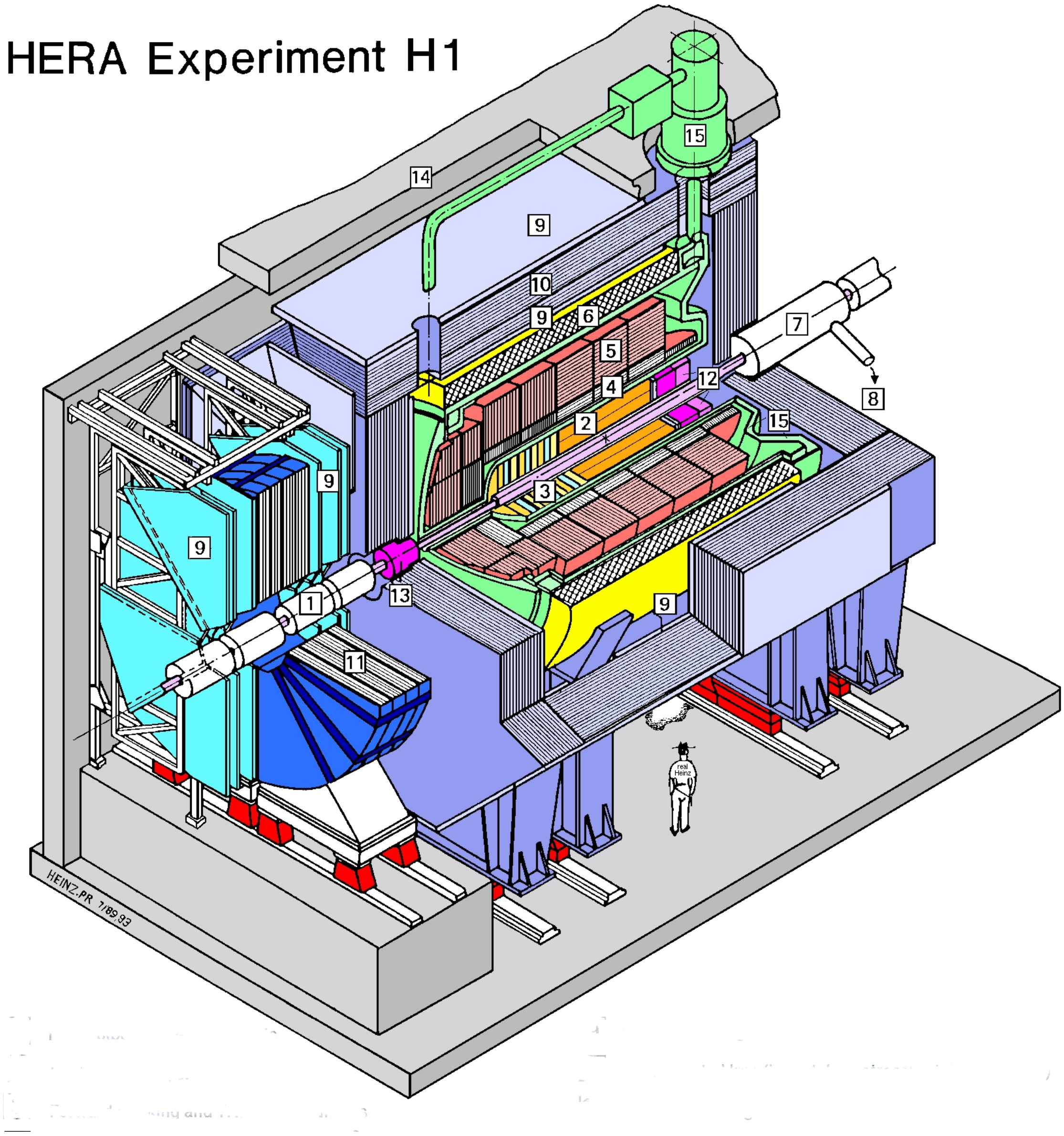

Figure 13: Layout of the H1 detector at HERA. The electromagnetic(4) and hadronic(5) LAr calorimeters are just next to the central tracker(2) and within the superconducting coil(6). The muons are measured in the muon chambers(9).

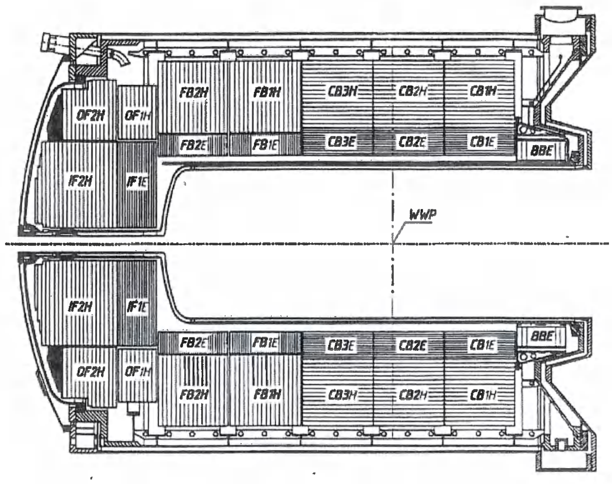

Figure 14: The r-z view of the H1 LAr calorimeter. Shown are the electromagnetic and hadronic sections of the LAr calorimeter. The high energy protons are entering from the right, the electrons from the left. The asymmetry in the energies defines the geometry of the set-up.

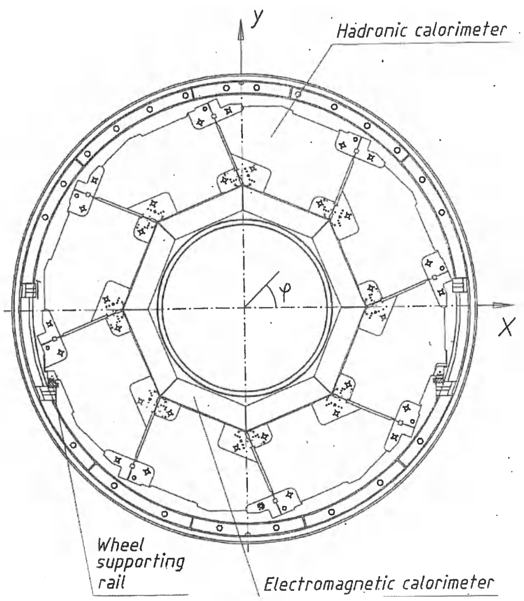

Figure 15: The $r - \phi$ view of the H1 LAr calorimeter. The ϕ cracks are pointing to the interaction point for the electromagnetic sections and non-pointing for the hadronic sections.

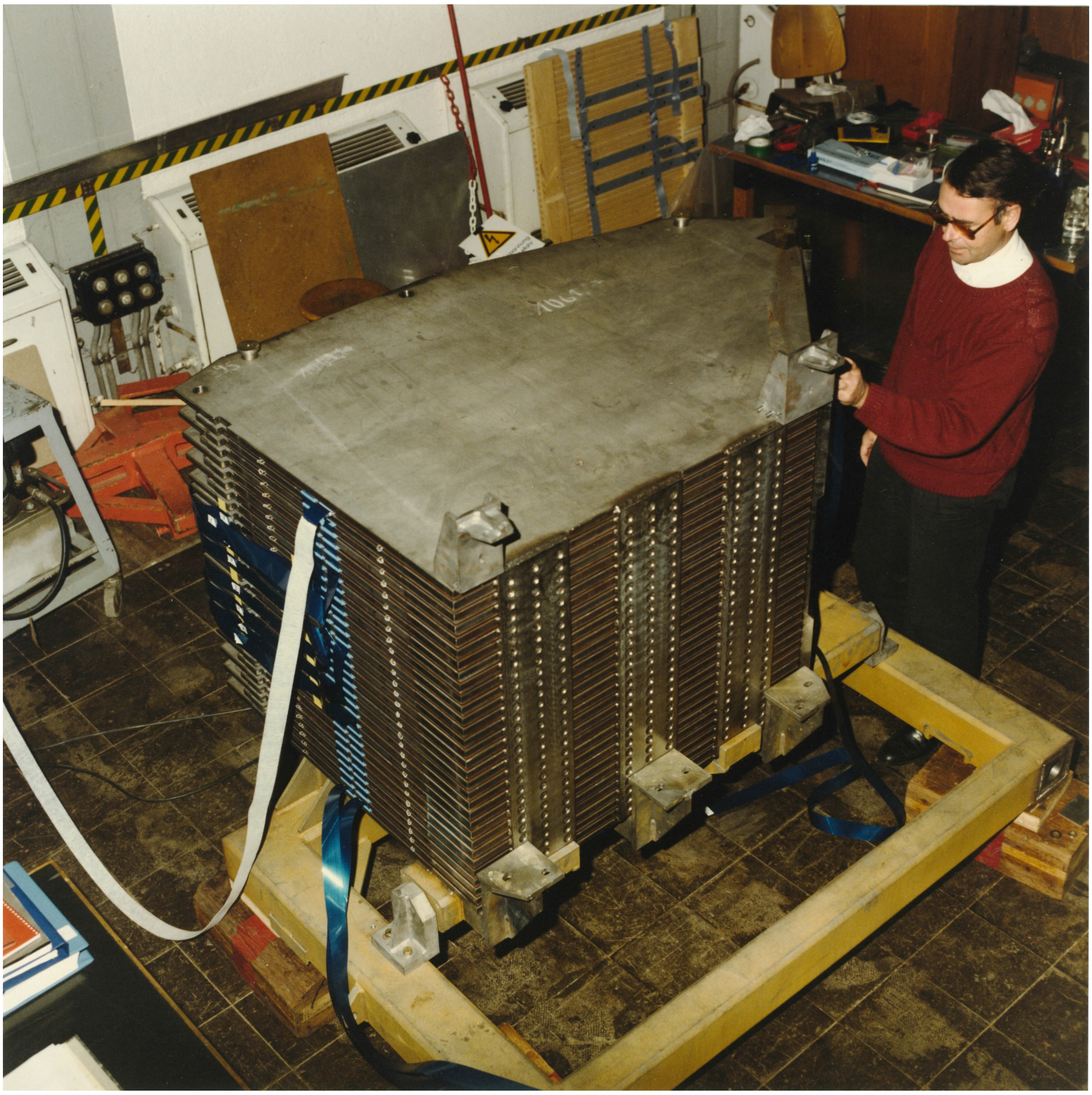

Figure 16: The first hadronic calorimeter module of the H1 calorimeter with the H1 calorimeter project leader H. Oberlack.

From ASCOT to ATLAS: the Route to the LHC

In 1990 started the preparation for the design of a detector at the pp storage ring LHC. The high luminosity with an unprecentended number of interactions per collision imposed a challenge for an optimal detector concept at that times. The muon reconstruction and trigger were therefore the first priority. The solution was an aircore toroid magnet with muon drift tubes. Next in priority was a good reconstruction of electrons and gammas, with the benchmark process of the Higgs boson decay $H \rightarrow \gamma\gamma$ in mind. The goal was an energy resolution for γ's of $\sigma/E = 9.5\%/E^{1/2} \oplus 0.5\%$ and an for hadrons of $\sigma/E = 50\%/E^{1/2} \oplus 2\%$ (with energy weighting). In close collaboration with the Rutherford lab the institute presented an expression of interest - ASCOT [30] (Apparatus with SuperCOnducting Toroids) - in 1992 at the CERN meeting in Evian. The spokesperson of the ASCOT collaboration was F.Dydak. The Fig.17 shows the schematic view of the detector.

For the LAr calorimeter small LAr gaps were proposed, to limit the charge collection time. As the drift time for ions is typically a factor of 1000 larger than for electrons, at very high luminosities the electric field in the LAr gap is severly distorted. Thus in view of the high luminosity a small LAr gap also guarantees to stay away from the critical ionization density in the forward region. Vice versa, small gaps increase the capacity, thus increasing the noise and worsening the signal to noise ratio. Therefore the concept of 'active pads' has been proposed: each signal from an individual pad is fed via preamplifiers in the cold to a summing stage (also in the cryostat). Thus the ganging in depth is done fully in cold. The development of cold electronics has been started in the calorimeter group already in 1990 and finalized in the RD33 test at CERN [32]. A second important aspect was the minimization of systematics. Keeping the impact angle relative to the absorber orientation almost constant within the full rapidity η-range the sampling ratio is almost constant and any losses due to cracks in $r-z$ can be avoided. With an impact angle of 45° this has been realized in the 'Thin Gap Turbine' (TGT) [31] in the η-region $|\eta| \leq 5.0$. The Fig.18 shows the TGT layout of the proposed ASCOT calorimeter in $r - z$. The size of the individual read-out boards is chosen to be rather small to be able to keep also the cracks in ϕ at a minimum. Three LAr double gaps, each 0.4 mm wide, two PB plates (1.6 mm thick) covered with thin stainless steel, three G10 read-out boards covered with high resistive polyimid and two outer stainless steel plates (2.0 mm thick) yield the basic read-out board unit. The cold preamplifiers are in small cutouts of the outer stainless steel plate. The pad signals are then routed to cold summing boards located at the outer periphery of the calorimeter. This concept has been tested with a calorimeter with 36 independent readout boards at CERN [32] and the requirements for the LHC were fulfilled.

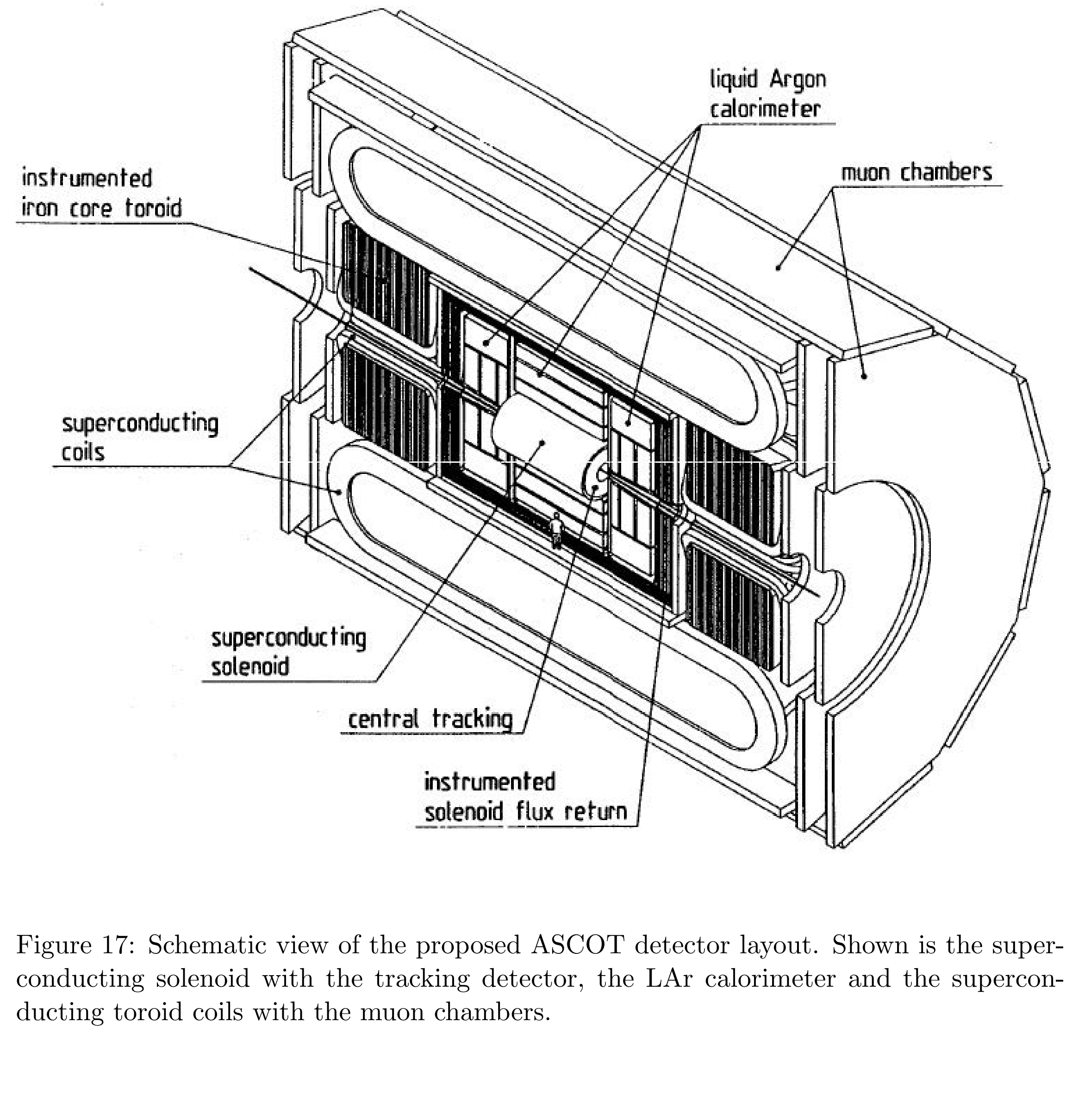

Figure 17: Schematic view of the proposed ASCOT detector layout. Shown is the superconducting solenoid with the tracking detector, the LAr calorimeter and the superconducting toroid coils with the muon chambers.

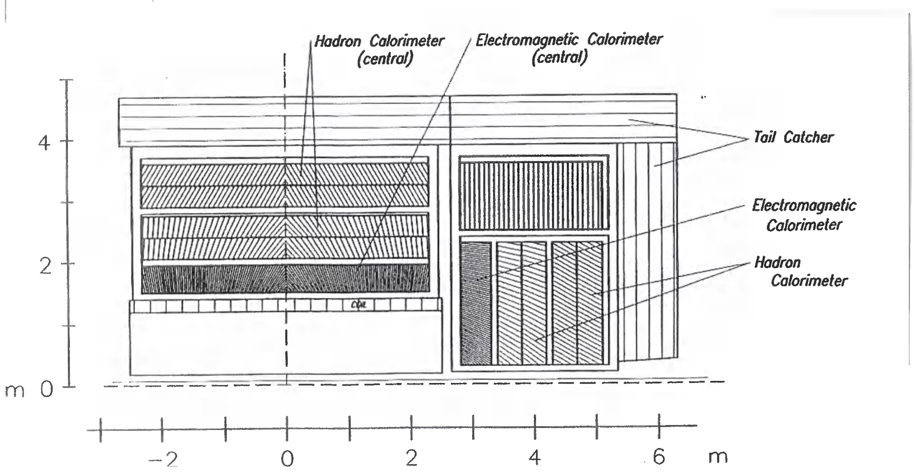

Figure 18: The r-z view of the proposed LAr calorimeter for the ASCOT detector. The absorber plate orientation is chosen to be at a constant angle of 45° relativ to the particle impact direction for the full range in z of the detector.

Following the Evian meeting CERN decided to support only two general purpose detectors at the LHC. Thus the collaboration had to merge with interested partners. A similar approach (LAr) for the calorimetry was proposed by the EAGLE collaboration, eventhough a warm Fe toroid has been chosen for the muon spectrometer. Both collaborations started discussions how to converge to one detector - the start of the ATLAS detector. In October 1992 the letter of intent [35] has been presented. For the muon spectrometer the aircore toroid has been kept, for the LAr calorimeter both options, the accordeon [33] and the TGT [34] have been kept. The final decision was planned to be taken at the ATLAS proposal [36].

Soon after a period of very intense discussions of various subgroups started in the ATLAS collaboration. Extrapolations of costs, systematic errors, feasibility, risks and manpower issues from the $R\&D$ phase to the final detector are always subject to large uncertainties. In consequence, many compromises had to be taken with difficult decisions. A strong impact came from the potentially available infrastructure and manpower of the interested institutions and the available funds. Finally in 1994 the agreement has been presented in the ATLAS proposal [36]. The Fig. 19 shows the layout of the ATLAS calorimeter. For the barrel hadronic calorimeter the TILE calorimeter option has been chosen, mainly for funding reasons. The electromagnetic calorimeter was chosen to be the accordeon option for the full coverage in η. The hadronic endcap calorimeter (HEC) with Cu absorber structure covers the forward region $1.5 < |\eta| < 3.2$. Finally the FCal calorimeter with tube geometry and Cu (electromagnetic) or W (hadronic) absorber structure covers the very forward region $\eta > 3.1$.

The calorimeter group of the institute focused finally on the HEC calorimeter. The construction work was shared with Canadian (TRIUMF/Vancouver) institutions and a German-Russian cluster. The preference for Cu rather than Fe as abosorber was mainly driven by rather cheap plate machinig in Canada due to free capacity of the oil drilling companies at that times on one side, and free workshop infrastructure in the Russian institutions. The European cluster, managed by the institute, got in addition strong support in funding by the European Community for the Russian industry (ISTC) or labs (INTAS). Thus the 16 mm thick Cu plates could be machined with the required precision in planarity and thickness. Also the concept of 'active pads' has been realized with the electronics in cold. The production of the electronics, which is after installation no more accessible, required an incredible carefulness in quality control: each chip (IC) prior to assembly has been cold tested, as well as the final PC boards and last not least the fully assembled stacks with the electronics. A large fraction of the modules has been actually tested at CERN in beams, providing important information for the calibration. The Fig.20 shows one HEC wheel on the assembly table prior to the vertical rotation. Finally one of the highlights of the LHC results and the ATLAS LAr calorimeter was the detection of the Higgs Boson H, and here in particular the decay $H \to \gamma\gamma$. The high precision measurement of the energy and direction of the γ offers a large discovery potential even in a harsh environment. The Fig. 21 shows the effective mass $m_{\gamma\gamma}$ of two γ's after background subtraction. Shown is the distribution for the discovery data as well as for the higher luminosity run 2 data.

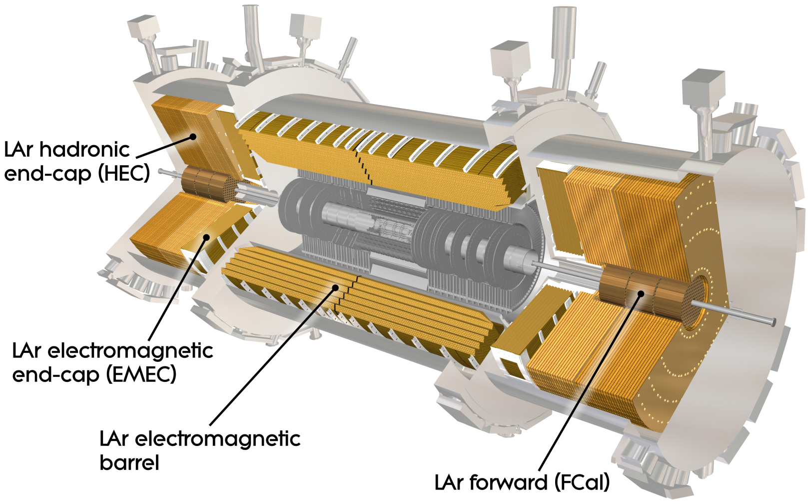

Figure 19: View of the ATLAS calorimeter system. Shown are the elctromagnetic and hadronic sections in the barrel as well as in the end-cap.

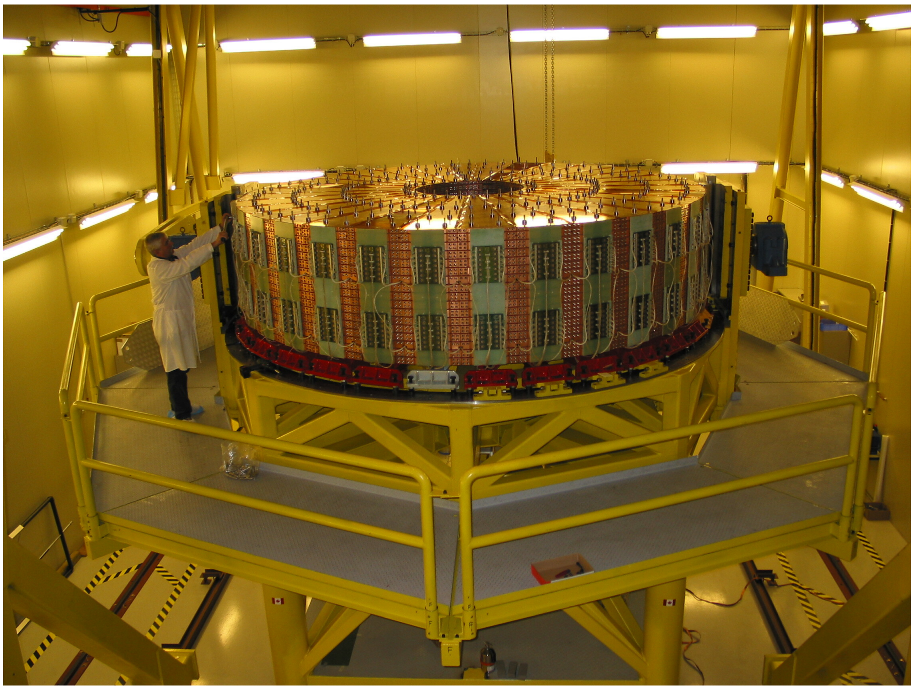

Figure 20: One HEC wheel on the assmbly table prior to the vertical rotation and insertion into the end-cap cryostat.

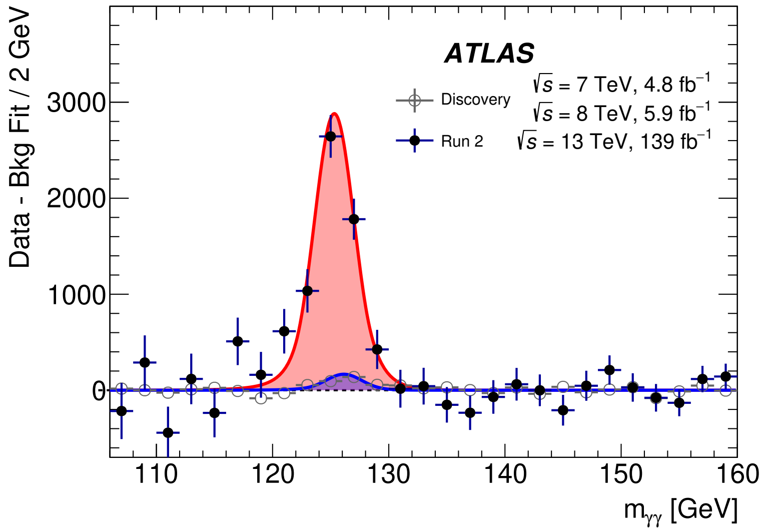

Figure 21: The decay of the Higgs boson $H \to \gamma\gamma$. Shown is the effective mass $m_{\gamma\gamma}$ of two γ's after background subtraction for the discovery data set and for the higher luminosity run 2 data.

4.3 The Future: from ATLAS at LHC/HL-LHC to the Future Circular Collider (FCC)

Presently ATLAS is upgrading the detector for higher luminosities expected at HL-LHC. But already the LHC luminosities triggered many optimization strategies to mitigate the pile-up in the calorimeter reconstruction of particles and jets. Using the tracking information or the timing information from calorimeter signals proved to be very successful. Thus for jets - after hadronic weighting - an energy resolution has been obtained for the transverse momentum $p_\perp$ of $\sigma_{p_\perp}/p_\perp = 23\% \oplus 2\%$ at 20 GeV or $\sigma_{p_\perp}/p_\perp = 6\% \oplus 0.5\%$ at 300 GeV.

In a next step jets are being reconstructed using both, the calorimeter as well as the tracking information. Thanks to the fine segmentation of the LAr calorimeter this approach turns out to be very promising. For jets with $p_\perp < 50\ GeV$ the energy resolution can be further improved by 10% - 20%.

The FCC is the future collider project at CERN, designed for 100 TeV in the hadron collider version (FCC - hh) or 90 - 400 GeV in the e^+e^- version (FCC - ee). With the FCC - hh planned at present the peak luminosity will increase further to $\mathcal{L} = 3 \times 10^{35} cm^{-2}s^{-1}$. In addition the higher energies yield larger boosts for jets. Physics at the EW scale is asking for high precision at lower energies in the range up to $\sim 100\ GeV$. On the other side at the high energy frontier a precision reconstruction of leptons and jets is required as well. Thus typical calibration signals as obtained from Z decays have to be scaled up few orders of magnitude. Both, the option to combine the calorimeter measurement with the tracker information as well as the large range in energy can be matched with the LAr technology: fine segmentation of the calorimeter and the excellent linearity and stability of the signal.

First concepts of a future FCC detector have been studied [37]. Following somewhat the ATLAS concept, the barrel electromagnetic calorimeter as well as the forward electromagnetic and hadronic calorimeters are in LAr technology. For the barrel electromagnetic Pb-calorimeter a non-standard absorber plate orientation with respect to the particle impact angle has been chosen: in ϕ the absorber plates are tilted by 50° with respect to the particle impact. This is somewhat similar to the TGT approach, but here the 'turbine' has been realized in ϕ rather than in η. This is reasonable due to the rather limited range in η. As in the TGT concept, this allows for a very homogeneous response and offers an optimal segmentation. To stay away from the critical ionization limit the gap width has been set to 1.15 mm. In the forward region $|\eta| > 1.5$ a planar geometry has been chosen. Here the gap is furthere reduced, up to 0.5 mm for the electromagnetic calorimeter in the region $|\eta| < 2.5$. For the very forward calorimeter $|\eta| < 6.0$ a gap width of 0.1 mm has been chosen. Here the required tolerances as well as radiation hardness of all the materials used, need a dedicated $R\&D$ study.

It is evident that the requirements in FCC on calorimetry are challenging. The LAr technology has a big potential to fulfil these requirements, eventhough detailed studies are needed before a final detector can be proposed.

5 Muon Detection at Colliders

5.1 The Muon Spectrometer of the ATLAS Experiment at the LHC

Muon detection with high efficiency is of special importance for the physics program at high-energy proton colliders, in an environment with high particle and hadron jet multiplicities. This is in particular true for the Large Hadron Collider (LHC), the world's highest energy collider, where the experiments attempt to detect extremely rare processes in an overwhelming hadronic background. High muon detection efficiency and momentum resolution was essential for the discovery of the Higgs boson at the LHC, its main goal, in the decay $H \to ZZ^* \to \mu^+\mu^- \mu^+\mu^-$ into four muons through two Z bosons decaying in to oppositely charged muon pairs. High muon momentum resolution up to muon energies of around 1 TeV is required for searches for new physics processes beyond the Standard model like decays of a heavy partner Z' of the Z boson into muon pairs or of supersymmetric partners of the Standard Model particles.

The design of the ATLAS detector (Figure 22)[39] pays special attention to precise and stand-alone muon measurement which was particularly emphasized by the MPP group when the experiment was founded. The muon spectrometer in a superconducting air-core magnet minimizing scattering material for the muons is a novelty for a collider experiment and distinguishes the ATLAS detector (Fig. 22) from the other LHC experiments. It allows for high muon momentum resolution over a wide energy range from 5 GeV to 1 TeV independent of other subdetectors. The name ATLAS, acronym for "A Toroidal LHC Apparatus", is derived from this outstanding feature. The MPP group strongly promoted such a detector concept, and initiated for this purpose a new detector proposal for the LHC in the early 1990s, called ASCOT ("Apparatus with SuperCOnducting Toroids"; see Fig. 17)[30]. MPP under the department director Friedrich Dydak formed a new experimental collaboration for participation at the LHC which included most of the high energy particle physics groups in Germany which at the time had still been undecided which experiment proposal to join.

Soon afterwards, the ASCOT concept was merged with another proposal–called EAGLE ("Experiment for Accurate Gamma, Lepton and Energy Measurements"), which also employed a liquid argon electromagnetic calorimeter and a toroidal magnetic field for the muon detector, although normal conducting and with iron core–to become the ATLAS experiment. The superconducting air-core toroid solution was retained for the new ATLAS detector. The independent high-precision momentum measurement in the muon spectrometer is especially important for ATLAS compared to its competitor at the LHC, the CMS ("Compact Muon Solenoid") experiment, as it has a two times weaker solenoidal magnetic field in the central tracking detector than CMS, which relies on the muon momentum measurement in the central tracker.

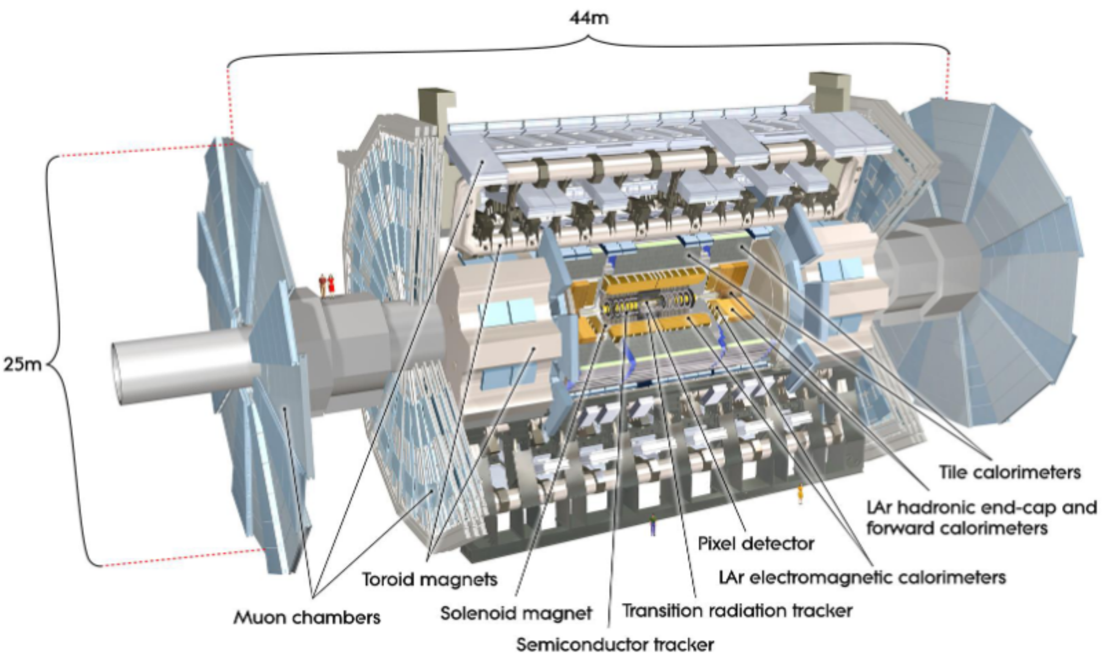

Figure 22: Cut-away view of the ATLAS detector dominated by the muon spectrometer with the barrel and endcap toroid magnets (grey) and the muon detectors (light blue) mounted on them. The muon spectrometer encloses the electromagnetic (orange) and hadronic (grey-green) calorimeters and the central tracking detectors (brown) which together are of the size of the ALEPH detector (chapter 2).

There are several unprecedented challenges for the ATLAS muon spectrometer under the experimental conditions at the LHC which were considered insurmountable by a large part of the high-energy physics community at the time. In order to achieve the desired 10% momentum resolution at the highest energies, the lever arm for measuring the muon track curvature in the magnetic field needed to be large, 6 to 10 m, making the superconducting magnet coils and the muon detection area huge, about 5500 m^2, equivalent to the size of a soccer field. Therefore, the muon spectrometer [40] determines the size of the ATLAS detector making it the largest collider experiment ever built, with a diameter in the central part of 25 m and a length of 40 m between the outer detector layers (Fig. 22).

The large detection area had to be instrumented with roughly 1200 muon detectors with unprecedentedly high spatial resolution of 40 µm, positioned in the vast spectrometer volume with similar precision. Additionally, the muon chambers have to cope with unprecedentedly high background radiation rates of low-energy neutrons and gamma rays which are created in the interactions of high-energy particles from the proton collisions in the calorimeters and the shielding material around the beam pipe of the LHC. The background radiation dominates the hits in the muon chambers by orders of magnitude. It not only deteriorates the muon detection efficiency and spatial resolution but can also cause aging of the detectors making them unusable over the foreseen long lifetime of the experiment of initially 10 years at the LHC and now in total 25 years, including operation at the high-luminosity upgrade HL-LHC starting in 2029. As most of the muon chambers can never be replaced and are very difficult to access for repairs, they need to be highly reliable.

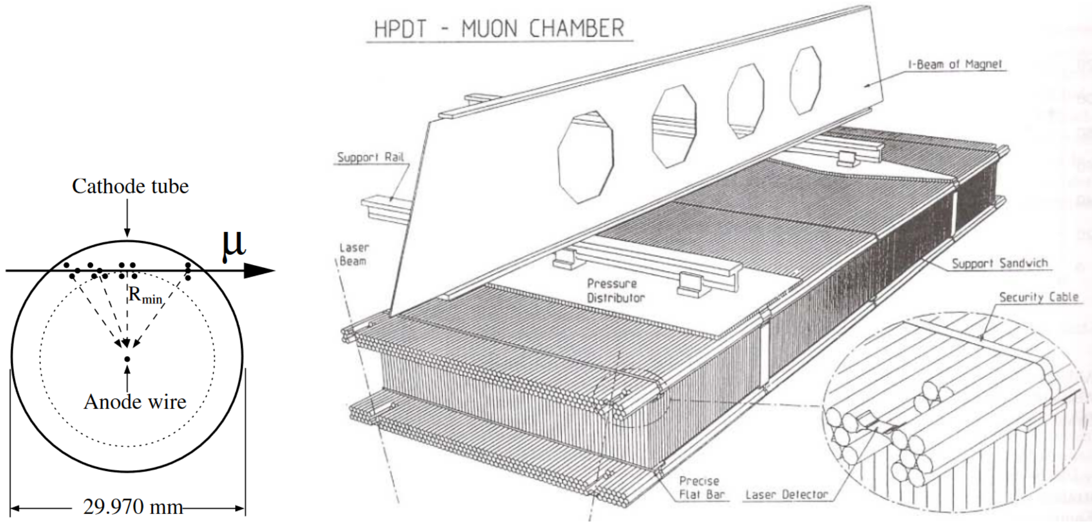

Figure 23: Left: Working principle of a drift tube: The ionization electron clusters created along the muon path in the gas drift in the electric field towards the anode wire. The drift time measured by the readout electronics is a measure of the distance of the muon track from the known wire position. Right: High Pressure Drift Chamber (HPDT) concept of MPP for the ASCOT and ATLAS experimental proposals [39] [**?**]. Several layers of drift tubes on either side of a support structure combine to measure a muon track segment with 40 spatial resolution if the sense wire position uncertainty can be neglected.

5.2 The Muon Drift Tube Detectors

The MPP group set out early on to design such robust high-precision muon tracking detectors. To cover the large areas at acceptable cost, gas chambers are the only option. It was realized that high mechanical precision and stability of the chambers was required. The MPP group, with Walter Blum as prominent representative, developed and strongly promoted the High-Pressure Drift Tube (HPDT) concept (Fig. 23) for the ASCOT experiment proposal [**?**] which was finally adopted by ATLAS in a fierce competition with several other proposals in the form of the Monitored Drift Tube (MDT) chambers, illustrated in Fig. 24. This was a great success for the MPP group; the acronym "MDT" was jokingly interpreted as "Munich Drift Tubes". In the following, the MDT chambers and the optical alignment monitoring system for the ATLAS muon spectrometer were designed at MPP, the first prototypes built and the largest detector construction project in the history of MPP brought on the way.

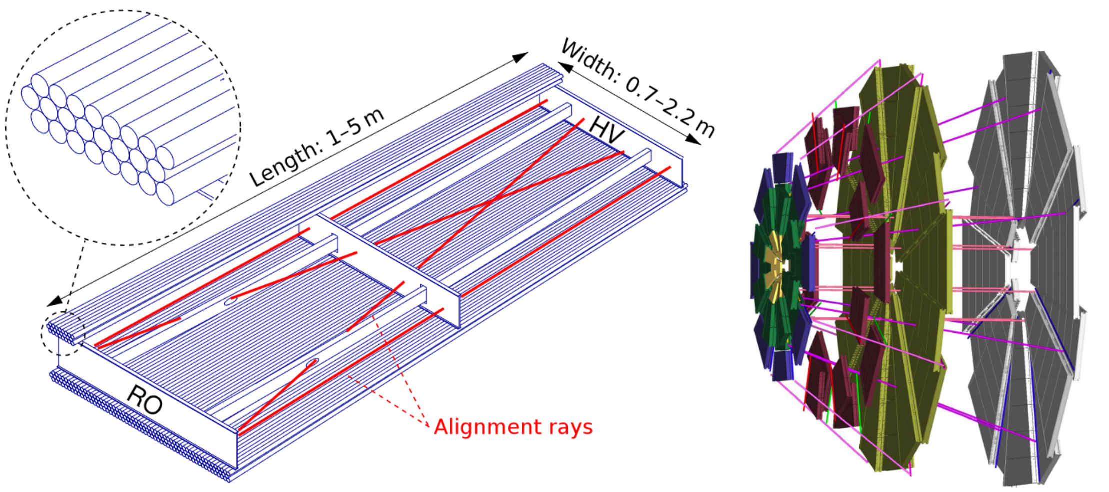

Figure 24: Left: ATLAS MDT chamber concept with light support frame containing the planarity monitoring system using light rays and optical position sensors. Right: Impression of the light ray network connecting the MDT chamber layers of one endcap muon spectrometer.

The ATLAS MDT chambers consist of two triple or quadruple layers of 30 mm diameter aluminum tubes separated by a light-weight support structure into which an optical planarity monitoring system is integrated. In total there are almost 140000 drift tubes in the ATLAS muon spectrometer. The tubes have only 400 μm thick walls and are filled with Argon gas with an admixture of 7% CO_2 at two bar overpressure. A voltage of 3080 Volt is applied between the aluminum tube wall and the 50 μm thin anode wire in the center of the tube. These so called drift tubes measure the time it takes for the ionization electrons created along the traversing muon tracks to drift to the anode wire in the radial electric field (Fig. 23). In the region of high electric field near the wire, secondary ionization avalanches multiply the charge by a factor of 20000 which is well detectable by the readout electronics connected to the wire. The drift time is a measure of the distance of the muon track to the sense wire. The drift detector principle allows for high spatial resolution with a minimum number of expensive electronic channels. The gas over-pressure significantly reduces the statistical fluctuations in the arrival time of the ionization electrons.

The individual MDT drift tubes achieve a spatial resolution of 80 μm. Combination of the measurements in 6 to 8 drift tube layers along the muon track leads to the required spatial resolution of 40 μm. This requires that the several hundred sense wires in a chamber are positioned with an accuracy of 20 μm, a mechanical precision which had never been achieved before on such a large scale. Initially, there was a wide-spread believe in the High Energy physics community that this would never be feasible.

Muon tracks are measured in the toroidal magnetic field in three layers of MDT chambers, the minimum for determining the muon momentum from the track curvature. For muons with 1 TeV energy the deviation of the tracks from a straight line over the distances of 6 to 10 m inside the muon spectrometer is only 100 μm. In addition to the high mechanical precision of the individual MDT chambers, their relative positions in the three layers of muon chambers, therefore, have to be known with similar precision of 30 μm at all times. This could only be achieved by continuously monitoring the relative MDT chamber positions at this level of precision using optical position sensors mounted on the chambers which are connected by a network of hundreds of light rays (Fig. 24). The optical alignment system was proposed and to a large extent developed by the MPP group under Hubert Kroha, then still a postdoc at MPP with limited contract. The development was funded by an INTAS program of the European Union. The design fulfilled the high expectations which originally appeared almost impossible to achieve for such a large detector system.

A whole sector of the muon spectrometer with MDT chambers and alignment monitoring system was tested in real size with muons from cosmic rays and from a high-energy beam of the Super Proton Synchrotron (SPS) at CERN under MPP coordination (see Fig. 26). This system test was essential for the successful installation and operation of the ATLAS muon spectrometer.

5.3 MDT Chamber Construction

The about 1200 MDT chambers for ATLAS with almost 140000 drift tubes were produced in a world-wide collaboration of 11 particle physics institutes over a period of 5 years between 2001 and 2006. The MDT chambers turned out to be reliable beyond expectations with only a handful of wires broken so far and no signs of aging effects. This was achieved by enforcing common strict quality criteria at all construction sites under the coordination of the MPP group. The drift tubes and chambers had to be assembled in clean rooms. The drift tube materials had to be carefully selected, and strict cleanliness had to be ensured at all times in order to avoid contamination of the drift gas which could lead to deposits on the sense wires, so called wire aging, under the unprecedentedly high background radiation doses at the LHC.

MPP accepted the responsibility for the construction of the 88 MDT chambers in the outermost layer of the central cylindrical (so called barrel) part of the muon spectrometer, comprising 37000 drift tubes altogether and covering an area of 700 m^2. The chambers consist of two triple layers of drift tubes of four meter length and are more than two meters wide (see Figure 6). They each contain about 430 drift tubes. MPP also supported the MDT chamber construction at the Joint Institute for Nuclear Research (JINR) in Dubna, north of Moscow, in the framework of a program of the European Union to support russian research institutes (INTAS) which allowed JINR to make its contribution to the construction of the ATLAS muon spectrometer. The MPP installed a clean room with an automated drift tube assembly station to produce the drift tubes both for the MDT chambers from JINR and from MPP (Fig. 26).

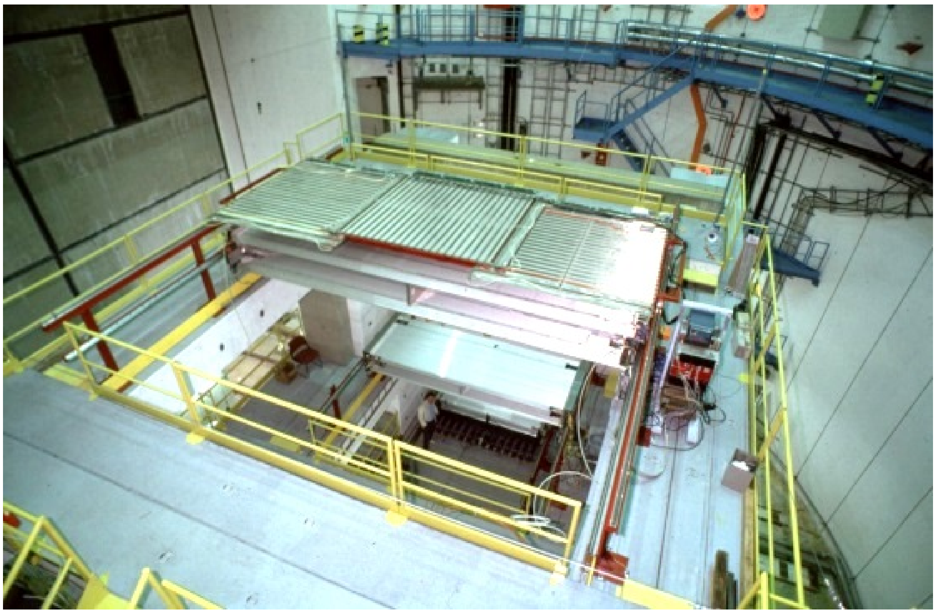

Figure 25: ATLAS muon system teststand at CERN in the former experimental hall of the UA1 experiment, installed and operated by Hans Dietl from MPP (on the floor at the bottom) from 1996 until 2000. The teststand consisted of a real-size sector of the ATLAS barrel muon spectrometer with three layers of prototype MDT chambers in operation.

Figure 26: Left: Visit of a CERN delegation consisting of the director of research Roger Cashmore and the leader of the theory department John Ellis in the clean room installed by MPP at JINR Dubna in 1999. Right: The clean room with automated drift tube assembly station installed by MPP at JINR Dubna in February 2000.

Figure 27: Left: The first MDT prototype chamber constructed at MPP in the new clean room in February 1998. The chamber dimensions are of the same size as for the series production. Right: Assembly of the first MDT chamber of the series production at MPP with the first prototype chamber in August 2000. The drift tubes of each layer are positioned in precise combs on the granite table. In the picture, the first tube layer has been glued to the support frame which has been lifted from the table. The support frame with glued tube layers can be rotated on the crane in order to successively glue the next tube layers to the top and bottom of the frame. The construction of the 88 chambers required for the outermost barrel layer of the ATLAS muon spectrometer was completed in December 2005.

Figure 28: MDT chamber storage and test with cosmic ray muons during the series production in a large hall rented in the north of Munich while storage space for the chambers was not yet availabe at CERN.

Figure 29: The team of physicists, engineers and technicians working on the MDT chamber construction and test in July 2001 after completion of 10% of the chambers.

The MPP group, under the leadership of Hubert Kroha, lead the design of the MDT chambers, of the precision construction methods and of the integration in the air-core toroid magnet from the beginning. The chamber construction method was strongly coupled to the design of the drift tubes themselves. The sense wires are positioned in the center of externally accessible aluminum rings surrounding the drift tube endplugs with an accuracy of $5\,\mu$m. This was verified for each tube end with an X-ray method. The tube endplugs were then placed layer by layer in combs also mounted with $5\,\mu$m precision on a polished granite table in a temperature controlled clean room (see Fig. 27). The fabrication of highly precise mechanical tools for the assembly of such large objects was new territory at the time. The development consequently took 5 years. The tube layers were alternatingly glued to the top and the bottom side of the support frame which was lowered to the combs for glueing and then lifted and turned around on a crane. During glueing together two adjacent tube layers, the gravitational deformations of the support frame on the crane had to be compensated with hydraulic pistons.

The sense wire positions are fixed relative to each other at the drift tube ends by the chamber assembly combs. Along the whole length of the tubes, the wire positions can then be predicted by precisely adjusting the wire tension during the drift tube assembly which determines the gravitational sag of the wire. The sag of the drift tube layers of each chamber under their own weight, monitored by the optical planarity measurement system (Fig. 24), was adjusted to the smaller wire sag using a mechanical strain mechanism in the support frame.

The MPP group designed and constructed the first MDT prototype chamber in 1998 (Fig. 27) [41], shortly after completion of the Technical Design Report for the Muon Spectrometer in September 1997, which was the result of a development period of five years. By scanning this prototype chamber with X-rays at CERN, it was demonstrated for the first time [41] that the required mechanical precision in the sense wire positioning of better than 20 μm could be achieved, allowing for the start of the MDT chamber series construction. Spot checks with the X-ray scanner of chambers from all construction sites confirmed the precision over the whole production period.

A completely new infrastructure with large temperature controlled clean room, large highly precise granite tables (Fig. 27) and and a large coordinate measuring machine for the verification of the mechanical precision had to be installed for the construction of such large and mechnically precise detectors. This was possible because of the strong support of the project by the managing director of the institute at the time, Volker Sö rgel. A large storage hall outside Munich had to be rented for the chambers during the series production (Fig. ??) because storage space for the chambers was not yet available at CERN. The functionality of the chambers over the long storage time was tested and analysed by many master and graduate students enthusiastic for the ATLAS project.

Several university grade mechanical engineers were hired for this project, a novelty for the institute's design office at the time, but indispensable for the complex engineering tasks in a complex environment like the ATLAS detector performed in international project teams. One of them, Klaus Fritsch, became project engineer of the ATLAS muon spectrometer project. Unfortunately he left the institute for another job just before the start of the MDT chamber series construction. The specially complex chambers with cutouts in the rectangular shape for letting cables passing through were then designed by a physicist, project leader Hubert Kroha himself.

The construction of the 88 MDT chambers of 2 m x 4 m size at MPP took five years from January 2001 to December 2005. This was the by far largest detector construction project in the history of MPP. During peak time, more than 15 technicians worked on the project. The team of technicians (Fig. 29) was coordinated by Alexander Wimmer who later became the head of the mechanical workshop. The competence of the institute's engineers and workshops was essential for the success of the MDT project and of the ATLAS detector construction as a whole. It was a challenge to maintain or even increase the level of competence for future projects.

In parallel to the chamber construction, the MPP group operated chambers in the system test stands with high-energy muon beams and in the Gamma Irradiation Facility at CERN. In the latter, the performance of complete MDT chambers under the irradiation conditions expected during the operation of the ATLAS detector at the LHC was evaluated. The studies showed the capability of the chambers to cope with the high background counting rates at the maximum LHC beam collision intensity, but also the limitations of the 30 mm diameter drift tubes in the case of an upgrade of the LHC to considerably higher proton collision rates.

The MDT chambers were integrated at CERN with dedicated gas detectors with high

Figure 30: Integration of the MPP MDT chambers with RPC trigger chambers and commissioning in a dedicated hall at CERN before installation in the ATLAS detector. Top left: MDT chamber storage at CERN. Top right: RPC chambers prepared for the integration with the MDT chambers in support frames designed and constructed at MPP. The distance between MDT and RPC chambers in the package had to be adjusted with millimeter precision under the same inclination angle as in the muon spectrometer to make the installation in the small available space possible. The rotation stand used for this purpose is visible at the top left in the picture at the bottom. The row of completed combined detectors can be seen in the foreground.

Figure 31: Top Left: Installation of an MDT chamber on the outside of a barrel toroid magnet cryostat at the top of the ATLAS detector. The chambers had to be lowered to the ATLAS cavern, inserted on rails mounted on the toroid coils and positioned with millimeter precision. Top right: Installation team of the MPP MDT chambers in the ”feet” region of the barrel muon spectrometer on the floor of the ATLAS experimental cavern. Bottom: Fine adjustment of an MDT chamber in the ATLAS muon spectrometer by a young female technician from MPP working in climbing harness at large height and in very cramped space.

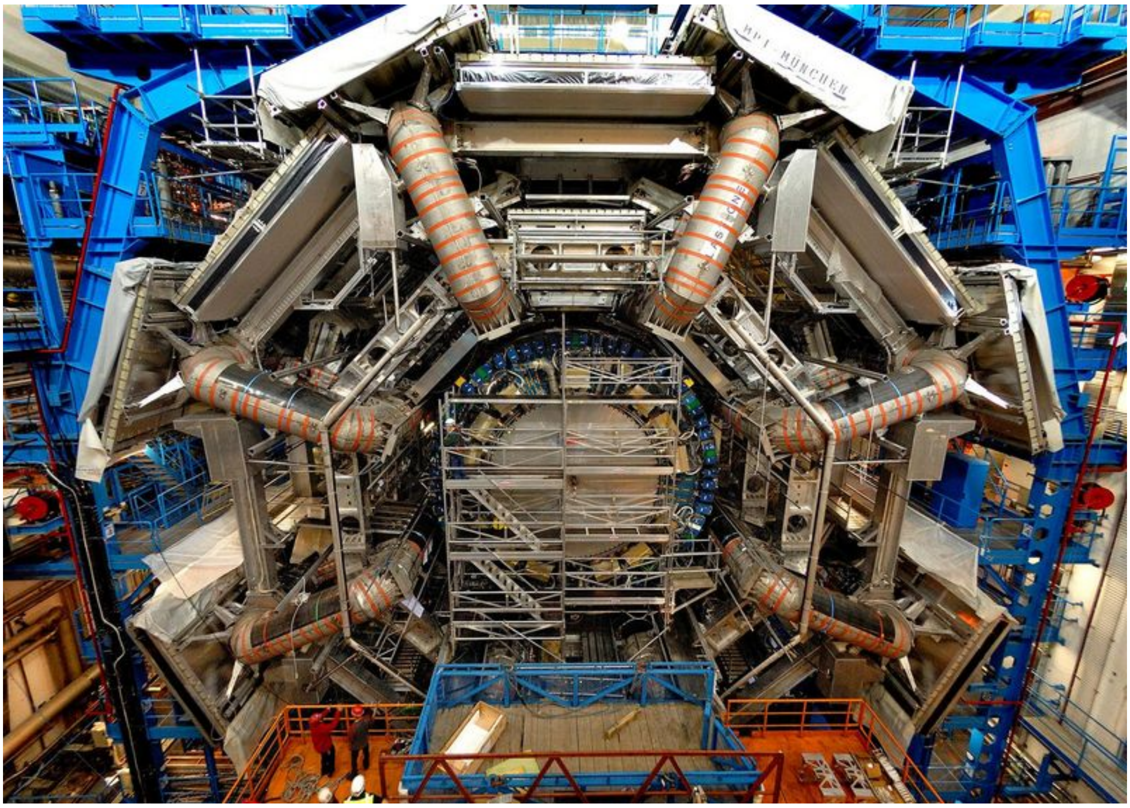

Figure 32: Completion of the barrel MDT chamber installation in June 2006. The MPP chambers are located in the outermost layer protected by covers. The enormous size of the ATLAS detector with a diameter of 25 m is apparent. The MPP PhD students, enthusiastic to help commission the chambers in the ATLAS cavern, expressed the pride in their work by installing a sign "MPI München" on a chamber well visible at the top right of the ATLAS detector in a height of 25 m.

time resolution (Resistive Plate Chambers, RPC), which deliver fast muon trigger signals for the readout of the MDT chambers, during one year between July 2005 and May 2006 (Fig. 30). The installation and commissioning of the MPP chambers in the ATLAS muon spectrometer took place from February to June 2006 (Fig. 32). The chambers had to be lowered individually through the access shaft to the ATLAS cavern 100 meters underground where they were shifted onto rails mounted on the toroid magnet cryostats and brought into their nominal positions with millimeter accuracy. The MPP installation crew consisting of physicists, engineers and technicians gathering at the ATLAS cavern floor is shown in Fig. 31.

5.4 Muon Drift Tube Chambers for the Highest Counting Rates

Already before the start of the ATLAS MDT chamber construction, considerations of a possible increase of the maximum proton collision intensity (luminosity) of the LHC by up to an order of magnitude got on the way. The upgraded version of the LHC was originally called Super-LHC (S-LHC), and later approved as High-Luminosity LHC (HL-LHC) in 2016 to start operation in 2029 after several steps of improvements. Based on the measurements of MDT chambers in a muon beam under high background irradiation at the Gamma Irradiation Facility at CERN performed by the MPP group from 2003 on, it became clear that the MDT chambers in the inner endcap layers and parts of the inner barrel layer would not be able to cope with the background counting rates increasing proportionally to the proton collision rate and consequently needed replacement.

At the same time, muon trigger chambers were needed also in the inner muon spectrometer layer to reenforce the muon trigger efficiency. The readout electronics of the MDT chambers had to be upgraded to cope with the higher trigger and data rates at HL-LHC. This would allow for a new continuous readout and MDT based trigger scheme, which was proposed by MPP [42] in order to improve the momentum resolution of the muon trigger in order to control the trigger rate of low momentum muons. The dedicated ATLAS muon trigger chambers, Resistive Plate Chambers (RPC) in the barrel and Thin Gap Chambers (TGC) in the endcap regions [39], provide much lower spatial and momentum resolution than the MDT chambers.

From 2008 on, the development of a new generation of precison muon tracking detectors with higher rate capability, sufficient for HL-LHC and potential future colliders, was advanced at MPP under the leadership of Hubert Kroha. This development led a few years later to another large-scale construction project for the upgrade of the ATLAS detector at HL-LHC. It turned out that the counting rate capability of the drift tubes can be improved by an order of magnitude [43], sufficient for operation at HL-LHC and future highest-energy proton colliders conceivable in this century, by reducing the drift tube diameter by a factor of two while maintaining the MDT operating parameters like gas composition, pressure and amplification, and by improving the signal processing of the readout electronics to avoid degradation or loss of the muon signals due to preceeding background signals.

In the course of these developments, the custom design of integrated circuits in modern chip technologies was established at MPP. With this competence, the MPP ATLAS group successfully developed the new readout chips for the ATLAS MDT chambers for the HL-LHC upgrade well before the official start of the ATLAS upgrade project [**?**]. The MDT readout chips are now being further developed for higher counting rates at future colliders and in modern chip technologies (Fig. 33).

The new drift tube chambers, known as small-diameter Muon Drift Tube (sMDT) chambers [43], have become a world-wide trade mark of MPP. They are one of the rare cases where the complete detector system, including dedicated readout electronics, has been designed by one and the same institute. With their high reliability and robustness as well as high background counting rate capability (far beyond HL-LHC requirements), they constitute ideal, cost effective muon precision tracking detectors for experiments at future high-energy proton colliders even beyond the HL-LHC.

With improved drift tube design for the smaller diameter, drift tube production became considerably cheaper and chamber assembly faster and more precise. A record sense wire

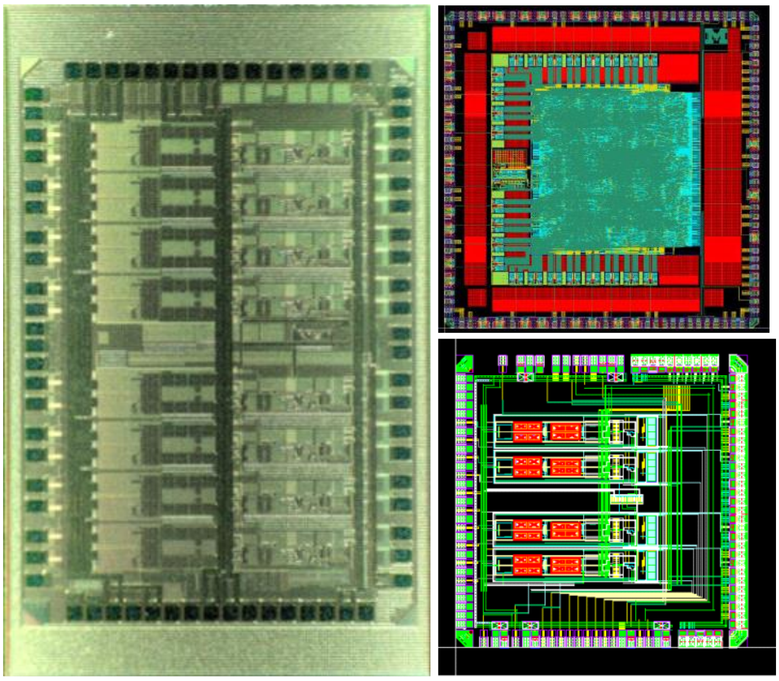

Figure 33: Examples of integrated circuit chips developed at MPP. Left: X-ray picture of the new readout chip for the MDT chambers at HL-LHC with eight channels in 130 nm CMOS technology. Top right: Time-to-digital converter chip for digitization of MDT drift time measurements at HL-LHC in 130 nm CMOS technology. Bottom right: Schematic layout of a new faster sMDT readout chip for high counting rates beyond HL-LHC at future colliders with four channels in 65 nm CMOS technology.

positioning accuracy of $5\,\mu$m was achieved in the sMDT chamber productions for ATLAS described below [43]. In the new sMDT drift tube design, all sense wire positions can be measured mechanically on the outside of the tubes at the endplugs using an automated coordinate measuring machine. This also allows for measuring potential mechanical torsion of the chambers around the tube direction to verify the predictions from the optical planarity monitoring system (Fig. 24).

5.5 Upgrades of the ATLAS Muon Spectrometer

The sMDT chambers immediately proved to be very versatile for complementing the ATLAS muon spectrometer in regions which could not be covered with detectors before. In total 22 sMDT chambers of different sizes and shapes were designed and constructed at MPP (Fig. 35) and installed for operation in ATLAS in 2013, 2016 and 2020 (Fig. 38) [43], before the upcoming upgrade for HL-LHC. A new semi-automated sMDT drift tube assembly facility was established for this purpose at MPP (Fig. 34). The sMDT chamber construction for the ATLAS upgrades already required only one third of the person power needed for the MDT chamber production. The sMDT team of physicists and technicians in summer 2022 is shown in Fig. **??**. The aim for the future is to completely automatize the drift tube and chamber assembly procedures. To make this development possible,

Figure 34: Clean room at MPP for the semi-automated assembly of the drift tubes of the sMDT chambers. The wires are fed through the tubes using air flow to avoid any manual contact and are tensioned with high reproducibility to guarantee equal gravitational sag of the wires in all tubes within 4%.

new high-level mechanical and electronics engineering capacity had to be acquired for the institute. Having achieved this is a milestone in the development of the Technical Department of MPP and will be instrumental for further leadership in detector development and construction for future international collider experiments.

The upgrade of the ATLAS detector for HL-LHC initially focussed mostly on the replacement of the silicon tracking system. The MPP group was the first one to point out early on the necessity of also an upgrade of the muon spectrometer which considerably improved the muon tracking and trigger efficiency under the expected 10 times higher background rates and extended the coverage of the solid angle around the proton-proton collision region in detector center [40]. The MPP upgrade proposal first resulted in the replacement of the two 20 m diameter wheels of the inner detector layers in the endcap regions of the muon spectrometer, completed in 2022.

The main muon detector upgrade for HL-LHC, which was approved by the ATLAS collaboration in 2017, comprises a complete replacement of the innermost layer of MDT chambers in the barrel region by sMDT chambers integrated with a new generation of RPC trigger chambers and the use of the MDT and sMDT chambers in the muon trigger system. The latter serves to improve the muon momentum resolution for the trigger decision by an order of magnitude compared to using the RPC chambers alone. It requires the replacement of the MDT chamber readout electronics and, thus, the design of new readout chips which has been carried out at MPP [45]. MPP also developed the new MDT muon trigger processors which for the first time perform muon track reconstruction in real time

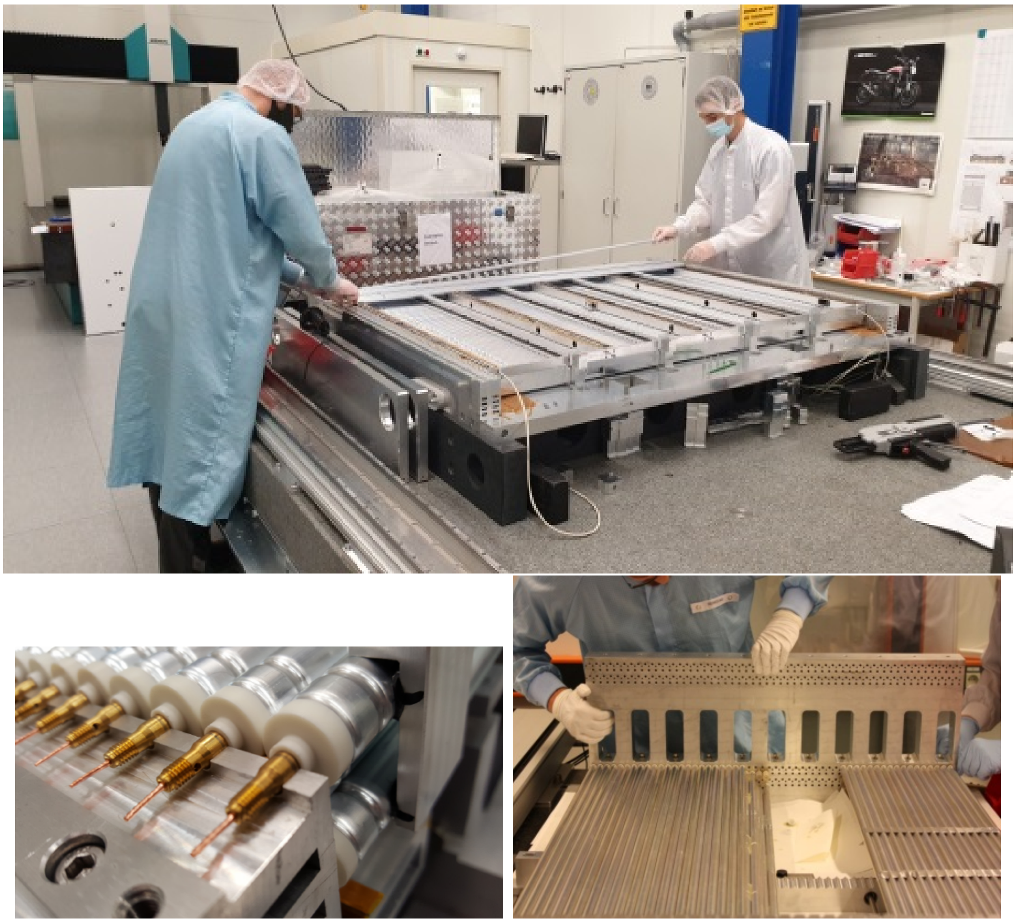

Figure 35: sMDT chamber assembly at MPP. The drift tubes are stacked layer-by-layer on top of each other by inserting the endplugs in precisely machined jigs (bottom) considerably speeding up the assembly procedure and increasing the wire positioning accuracy. The sMDT chamber assembly can be performed by technicians without special training and lends itself for automatization in the future.

within less than a microsecond [46].

For the muon spectrometer upgrade for HL-LHC, Hubert Kroha and the MPP group formed a collaboration of institutes experienced in muon detector construction for the original ATLAS muon detector. The group at the University of Michigan in the United States constructed half of the 96 sMDT chambers needed for the replacement of the MDT chambers in the inner barrel. These chambers were designed and their construction coordinated by MPP. The chamber production at MPP started in January 2021 and was completed in December 2022 as the first ATLAS upgrade project for HL-LHC. The University of Michigan followed 7 months later. The chambers are now all at CERN (Fig. 39), waiting for the installation of the new readout electronics boards designed by MPP and in production, and for the integration with the new RPC chambers. German university intitutes in Munich (LMU), Würzburg and Mainz committed themselves to financing and testing of the sMDT readout electronics boards.

Figure 36: sMDT chambers in various stages of completion in the construction hall in the old MPP building in Munich. After the assembly out of the drift tubes, the gas connections to each individual drift tubes are installed. More than 5000 rubber sealing rings each chamber have to fullfill very high gas tightness standards. By design this worked almost every time in the first attempt. Afterwards, the readout electronics boards and Faraday cages protecting them are installed. The teststand for the final certification test with cosmic ray muons in visible in the background of the pictures.

Figure 37: The team of physicists and technicians working on the sMDT chamber construction and test in March 2023 after completion of the sMDT chamber construction for ATLAS at HL-LHC at MPP.

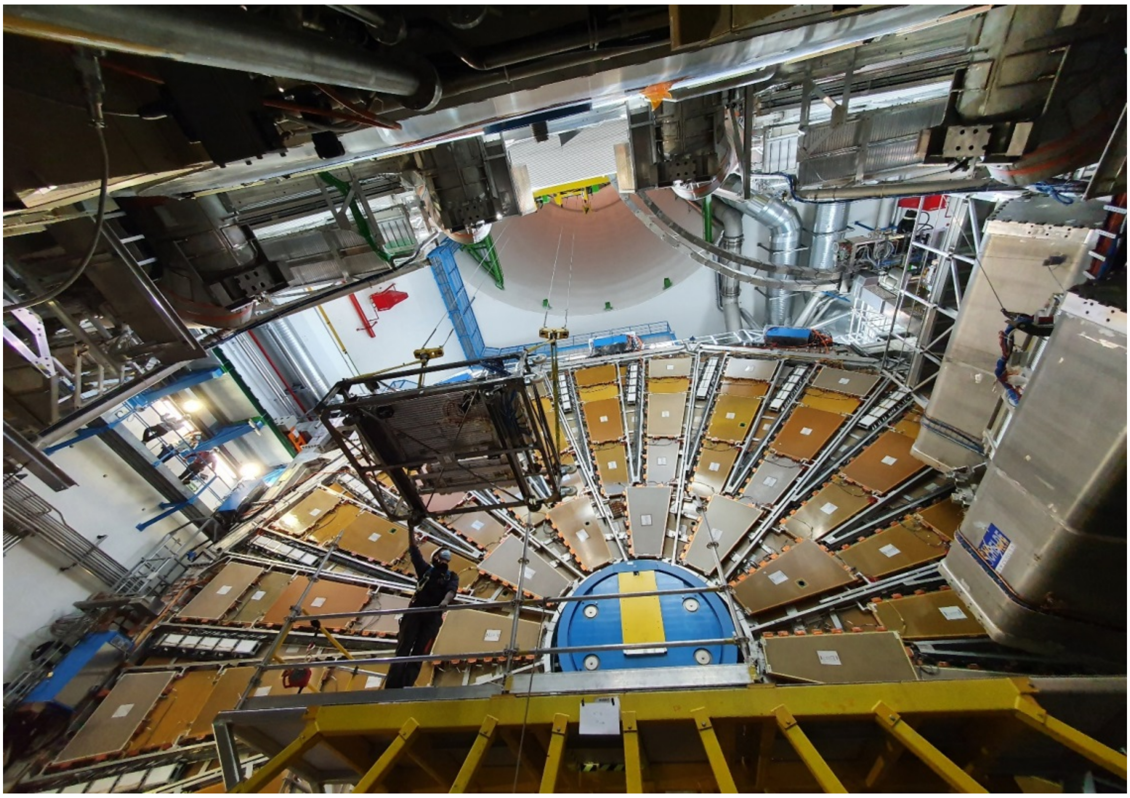

Figure 38: Installation of 8 sMDT chambers in the barrel inner layer of the ATLAS muon spectrometer in the fall of 2020 during a long shutdown of the LHC. The chambers are lowered one by one to the ATLAS cavern 100 m underground, in between the barrel spectrometer and the big wheel of the middle endcap muon chamber layer, which has been retracted for the chamber installation together with the endcap toroid magnet cryostat. The latter is visible on the right edge of the picture taken from the ATLAS cavern floor. The MPP group was one of the few actors at CERN during this critical period.

The Institute for High Energy Physics (IHEP) in Protvino, south of Moscow, played an instrumental role for the sMDT chamber construction in providing experienced technicians for the drift tube production and testing at MPP from 2017 until February 2021 when the collaboration abruptly came to an end. IHEP Protvino also delivered the mechanical parts for the sMDT chambers according to the MPP design from a large part of the russian funding contribution to the the ATLAS upgrade. The deliveries were completed in April 2021, in the last possible moment before the borders were closed for trucks from Russia.

MPP also took over the responsibility for the design and production of a quarter of the about 1000 new RPC detectors required for the ATLAS muon spectrometer upgrade for HL-LHC. Without the engineering contributions of MPP to the RPC project, the upgrade of the ATLAS muon spectrometer for HL-LHC could not have been realised. The MPP group embarked in the development of new construction methods for the new generation of RPC detectors, suitable for reproducible large-scale industrial production. Triplets of the new RPC detectors for ATLAS will also be assembled at MPP in mechanical support frames designed by MPP. By means of those, the RPC triplets will be combined with the

Figure 39: sMDT chambers built at MPP for the upgrade of the ATLAS muon spectrometer for HL-LHC in the assembly hall at CERN where they are waiting for the delivery and installation of the new readout electronics and for the combination with the new RPC detectors, the construction of which is to start at MPP in 2024.

sMDT chambers before installation in the ATLAS experiment. The design of the RPC support frames was challenging because they have to provide enough stiffness to hold the stacks of RPC detectors together withing very little space of only 5 cm height in the inner barrel layer of the muon spectrometer.

The RPC construction technology has been successfully transferred to two german companies where the construction for ATLAS will start end of 2024. Together with the new RPC construction facility at MPP (Fig. 42), this will be a great asset for the High Energy Physics community at large to support future large-scale RPC detector construction projects. RPC chambers have applications in a wide range of particle physics experiments as large-area tracking detectors with high time resolution and moderate cost, from cosmic ray detector arrays to collider experiments.

Triplets of the new RPC detectors for ATLAS will also be assembled at MPP in mechanical support frames designed by MPP with which they will be combined with the sMDT chambers before installation in the ATLAS experiment.

5.6 Highlights of Physics with the ATLAS Muon Spectrometer

In parallel with the detector construction and installation, the MPP group prepared for the time of the first proton collisions at the LHC and the start of data taking with the ATLAS experiment, in order to be at the forefront of the data analysis and potential discoveries at the highest center-of-mass energies achieved to date. The first important step was understanding the operation of the complex detector system and the correct interpretation of the data. Years were spent with studies and gradual improvement of the simulation of proton-proton interactions in the new uncharted energy regime and of the details of the detector response. One of the so called Tier 2 computing centers, used for processing and analysis of the ATLAS data, was installed at the computing center of the Max Planck Society in Garching and operated by MPP.

The MPP group made decisive developments for the in-situ calibration of the space-to-drift time relationship of the MDT chambers in ATLAS and of the muon momentum measurement in the muon spectrometer using $Z \rightarrow \mu^+\mu^-$ decays as standard candle, which are copiously produced at the LHC. For the continuous calibration of the 140000 MDT drift tubes, a dedicated computing cluster was established at the computing center of the Max Planck Society in Garching together with the Tier 2 center.

The high momentum resolution of the ATLAS muon spectrometer is instrumental for the efficient detection of the Higgs boson in its decay into four muons. The "golden" decay channel $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ \ell^+\ell^-$ into two oppositely charged electron-positron and muon-antimuon pairs ($\ell^+\ell^-$) originating from the decays of two intermediate Z bosons was decisive for the discovery of the Higgs boson in July 2012 (Figs. 40 and 41), together with the decay into two energetic photons $H \rightarrow \gamma\gamma$ (see Fig. 21) [48][49]. The discovery took place shortly after the start of data taking in 2010, still at proton collision energies of 7 and 8 TeV which is only half of the design value. The Higgs boson search with the ATLAS experiment leading to the discovery was coordinated by Sandra Kortner from the MPP group, a former master and graduate student of Hubert Kroha in the ATLAS project now leading an independent research group on ATLAS data analysis.

The Higgs boson discovery was confirmed after the increase of the collision energy to 13 TeV, close to the design value of 14 TeV (Fig. 40) [50]. The high muon momentum resolution and precise calibration of the muon spectrometer allowed for the most precise measurement of the mass of the Higgs boson in the decay channels into four electrons and muons. Together with the precise measurement of the mass of the top quark, the heaviest known particle interacting strongest with the Higgs boson, for which the MPP group alos has been instrumental in the ATLAS experiement, the measurement of the exact mass of the Higgs boson is decisive for the range of validity of the Standard Model at energies above the LHC.

The MPP group successfully aspired to play an instrumental role in the discovery of the Higgs boson, the at the time last undiscovered particle predicted by the Standard Model and the main physics target of the experiments at the LHC. In particular, the study of the Higgs boson decay into four muons with the aim of identifying possible deviations from the Standard Model predictions is a domain of MPP. MPP also plays an important role in the precise measurement of the mass of the top quark, the heaviest known particle, with which the Higgs boson interacts most strongly.

The new energy regime accessible at the LHC also opened up the opportunity to find other new particles predicted by theories extending the Standard Model in order to explain some of the many open questions. Extensions with so called Supersymmetry, relating matter constituent particles to the particles carrying the forces between them, are most promising. Supersymmetry predicts a partner particle for each Standard Model particle. It can explain the small mass of the Higgs boson compared to the expectations from the Standard Model and provides candidates for the particles of Dark Matter in the universe. The search for supersymmetric partner particles decaying into multiple muons was pioneered by MPP.

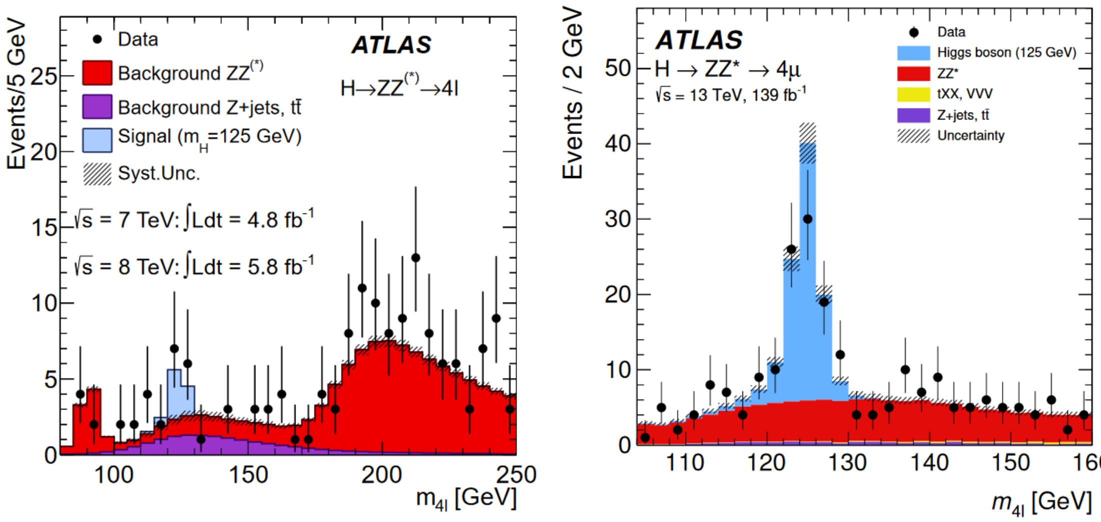

Figure 40: Left: Mass spectrum of four-lepton events contributing to the discovery of the Higgs boson in July 2012 at proton-proton collision energies of 7 and 8 TeV. The excess of events above the expected backgrounds at a mass value of 125 GeV/c^2 indicates the Higgs boson resonance, underlayed by the expectation (light blue) from the Standard Model of Particle Physics [48]. Right: Mass spectrum of four-muon events with 10 times more data from the LHC run at 13 TeV collision energy in the years 2016 to 2018 [50]. The Standard Model expectation for a Higgs boson mass of 125 GeV/c^2 is overlayed in light blue.

The rare decay of the Higgs boson into one oppositely charged muon pair, which requires especially high muon momentum resolution at high energies, is now at the verge of observation at the LHC. The increase of the proton collision rate at HL-LHC by a factor of 5 will allow for the detection of rare Higgs boson decays as well as of possible small deviations of the Higgs boson properties from the Standard Model predictions. Of particular interest is to further constrain the peculiar self-interaction of the Higgs boson which is resonsible for the spontaneous breaking of the gauge symmetry of the electroweak interaction in the Standard Model providing masses to the mediators of the weak interaction, the W and Z bosons. Searches for even more rare processes in the Standard Model and beyond will continue.

5.7 Gas Tracking Detector Developments for Future Experiments

The development of industrial methods for large-scale RPC chamber production places MPP in a central position for future applications of these detectors. In particular, the application of this technology in experiments at future high-energy electron-positron and

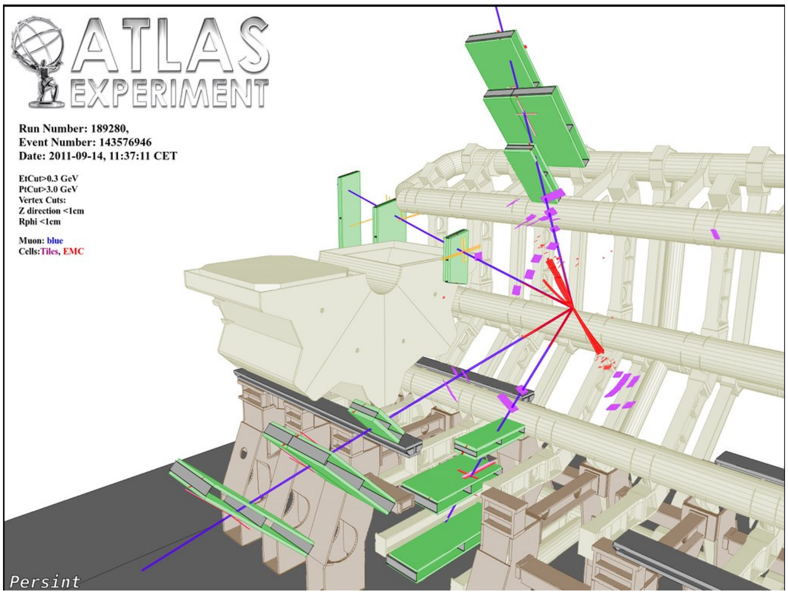

Figure 41: Cutaway electronic display of a Higgs boson decay into four muon tracks (purple lines) reconstructed in the three MDT chamber layers (green) in the barrel and one endcap of the ATLAS muon spectrometer [49]. Only the MDT chambers hit by the muons and part of the toroid magnet coils are shown.

proton-proton colliders are of high interest for MPP.

Gas detectors will continue to be the detector technology of choice for large area coverage in muon detectors and calorimeters at any collider experiment. sMDT detectors are ideal precision muon detectors under the even higher background radiation at future proton colliders [51] and can provide stand-alone muon trigger capability with high momentum resolution and selectivity against the vast low-energy muon background. The development of a muon track trigger based on the MDT and sMDT chambers in ATLAS for HL-LHC can be seen as a pilot project for such a future standard.

RPC detectors with their high time resolution and cost effective coverage of large areas are needed for the detection of long-lived particles decaying at the edge of the detectors. Gas drift detectors containing very little scattering material are needed for the central tracking detectors at electron-positron colliders to provide very high spatial and momentum resolution for charged particle tracks.

Future high-energy collider experiments present new challenges in precision, speed and radiation tolerence for the detectors and their readout electronics. The MPP group started the development of gas tracking detectors in the framework of the conceptual studies for experiments at Future Circular electron-position and proton-proton colliders at the highest center-of-mass energies planned at CERN and called FCC-ee [53] and FCC-hh [54], respectively (see chapter 5).

The MPP group contributed to the conceptual design of a detector [54] for a future FCC-hh proton-proton collider with 100 TeV center-of-mass energy and a circumference of almost

Figure 42: Top: Detector construction facility in a temperature controlled clean room at the new MPP building on the MPG campus in Garching in operation since the beginning of 2024. Large sMDT and RPC detectors will be contructed on polished granite tables using high-precision mechanical jigs and automatized robotic devices. The automated coordinate measuring machine is visible on the right. Bottom: The glueing robot in action on the assembly table for sMDT and RPC detectors.

100 km. The proton collision rate and the corresponding background rates in the detectors will be at least an order of magnitude higher than even at the HL-LHC. At the moment, only calorimeters based on liquid argon as active material (see chapter 3) can be conceived to withstand the harsh radiation conditions.

The selection of high-energy muons from the overwhelming background even in the muon detector requires unprecedentedly high muon momentum resolution in real time during the data taking. This is a new challenge compared to the ATLAS experiment, where the high muon momentum resolution provided by the MDT chambers was originally only required in the offline muon track reconstruction.

Once again, the sMDT chambers provide the ideal solution also as high-precision muon trigger detectors in combination with the central tracking detector for which a working concept under FCC-hh conditions has yet to be found. To this end, sMDT chambers have to measure the deflection of the muons in the magnetic field of the central tracking detector right after their passage through the calorimeters with unprecedentedly high precision. Deviations from vertical incidence of less than 70 μm have to be resolved over typically a meter distance between two successive sMDT detector layers. As the measurement has to be performed in real time, alignment corrections from an optical monitoring system like in ATLAS cannot be applied. The sMDT chamber layers at FCC-hh have to be build in monolithic pieces with perfect alignment and without deformations. This is only possible using the sMDT technology in a monolithic design of two multi-layers of drift tubes separated by an extraordinary stiff support frame of up to 1.7 m height and overall better than 20 μm sense wire positioning accuracy [51].

At the same time, the sMDT chambers have proven to provide radiation tolerance and background rate capability which is more than sufficient for even FCC-hh conditions [51]. The sMDT readout and trigger scheme developed at MPP for the upgrade of the ATLAS detector at HL-LHC can be directly employed also for the real-time muon direction and momentum measurement at FCC-hh.

A new facility for large-scale gas detector construction with high degree of automatization has been created in the new institute building in Garching (Fig. 42). The construction of a large prototype sMDT muon tracking and trigger chamber for FCC-hh is on the way using this facility. Studies of new electrode materials and gas mixtures with low global warming potential for RPC detectors which can tolerate high irradiation doses are on the way.

For all such detectors at future colliders, new fast, radiation hard readout electronics with integrated circuit chips in modern chip fabrication technologies are required. In the course of the developments for the ATLAS HL-LHC upgrade, the MPP ATLAS group and the MPP electronics department are set up to make significant contributions to these developments. Robert Richter from the MPP group, ATLAS MDT electronics coordinator until the start of data taking, was indispensible for the further development of the MDT readout electronics for HL-LHC and for future colliders and for establishing chip design capabilities at MPP.

The MPP group pioneered studies of the performance of drift tube detectors and their readout electronics at high counting rates. The full high-rate potential of the sMDT chambers at future colliders can only be exploited with faster readout electronics beyond the design for the ATLAS upgrade which is already faster than the original MDT readout electronics and more than sufficient for HL-LHC. Since more than 10 years, the MPP ATLAS group works on the further improvement of the rate capability of gas detector electronics, a research program which does not exist anywhere else.

Fast, sophisticated trigger algorithms are under development, which can fully exploit the information delivered by the ever more granular detectors within microseconds. The implementation of neural network and other artificlial intelligence algorithms on the fast programmable real-time processors (FPGAs) in order to further improve the trigger selectivity in increasingly complex environment is part of the MPP reserach program.

6 From ATLAS to Future Colliders

The HL-LHC will significantly extend the measurement precision of the LHC for parameters and rare processes in the Standard Model and the reach of searches for new phenomena beyond the Standard Model. It is the natural extension of the LHC. In parallel, however, the preparation for new colliders with capabilities beyond the HL-LHC has to take place as the planning and construction time for such unprecedentedly large and complex projects, which require world-wide collaboration, is several decades.

New high-energy colliders after the HL-LHC are under discussion since even before the approval of the LHC. Various linear electron-positron collider technolgies and, more recently, also circular electron-positron colliders, have been proposed with center-of-mass energies sufficient for resonant production of the Higgs boson at high rates. The study of the properties of the Higgs boson with ever higher precision is considered to be one of the most promising portals to the discovery of physics beyond the Standard Model and answers to the many questions it still leaves open.

After the revolutionary findings by the LHC experiments, the construction of such an electron-positron "Higgs factory" is now the top priority of the High Energy Physics community in Europe, and in the world, for the time after the HL-LHC. The design favoured at CERN is a circular collider with about 100 km circumference which provides a center-of-mass energy reach from the Z resonance near 90 GeV through the Higgs boson resonance at 125 GeV upto the top quark pair production threshold around 350 GeV. It will provide high-precision model-independent measurements of Z, Higgs and top quark properties, measurement of the Higgs boson self coupling, and searches for new phenomena up to very high energy scales through higher order radiative processes [52]. The required accelerator technology and a detailed conceptual design study for such a Future Circular e^+e^- Collider (FCC-cc) [53] are already available.

Afterwards, in the same tunnel, a new proton-proton (hadron-hadron) collider with center-of-mass energy of 100 TeV could be built, using the strategy applied for the construction of the LHC in the former LEP collider tunnel. Such a high-energy hadron collider, named FCC-hh [54], can provide the highest precision for testing the Standard Model and ultimate reach for new physics in this centuary. It would allow for a significant measurement of the self-coupling of the Higgs boson through Higgs boson pair production and, thus, detailed study of the electroweak symmetry breaking mechanism, and say the final word about the particle composition of the Dark Matter in the Universe and many proposed extensions of the Standard Model [52]. The FCC-hh is based on known accelerator technology. It requires the development of new superconducting dipole magnets which support twice the magnetic field strenght of the LHC magnets for which a rigorous research program is on the way.

Several detector concepts exist for a future high energy e^+e^- collider covering the center-of-mass energy range from the Z resonance near 90 GeV through the Higgs resonance at 125 GeV upto the top quark pair production threshold around 350 GeV, generally called a "Higgs Factory". In addition to highly granular calorimeters with unprecedentedly high energy and time resolution, they require unprecedentedly high momentum resolution for charged particles in the central tracking detector and precise muon detection over large areas with high time resolution.

The MPP ATLAS group has competence for all detector types and experience in the realization of large-scale detector construction projects. Research and development for innovative high-performance detector concepts for future colliders has started. World-class detector construction facilities have been created at the new institute building where large-volume detectors as required for future collider experiments can be built in temperature controlled clean rooms.

With the expected more than 10 times luminosity and radiation rates at FCC-hh compared to HL-LHC, calorimetry based on liquid argon currently appears to be the only choice with sufficient radiation hardness. A design of highly granular electromagnetic and hadronic liquid argon calorimeters in the barrel and forward regions following the TGT concept has been studied [37]. A similar approach may also provide a competitive solution for a FCC-ee detector with optimum segmentation and homogenuity η [37], the 'turbine' being realized in ϕ rather than in η for an e^+e^- collider experiment.

The central tracking detector at an e^+e^- collider needs to combine very high mechanical accuracy with minimum scattering material deflecting the traversing particles in order to achieve the unprecedentedly high required spatial resolution. The expertise from the sMDT chambers helps in the development of a central tracking chamber for FCC-ee consisting of small-diameter, so called straw drift tubes with very thin walls of low-Z material.

The muon detectors of FCC-ee experiments not only need to cover large areas but also have to provide very good time resolution for the reconstruction of tracks of long-lived particles. The RPC detectors developed for the ATLAS upgrade at HL-LHC are a competitive choice for which the MPP ATLAS group has extensive experience. Novel types of RPC chambers with even higher time resolution of better than 100 ps may be used for time-of-flight measurements and particle identification.

For muon detection and triggering at FCC-hh, sMDT detectors with novel fast readout electronics under development are at present the only conceivable choice for most of the solid angle.

The MPP ATLAS group is well prepared for challenges in detector design and construction for future high-energy lepton and hadron colliders in the next several decades and related applications in other experiments promising to help understand the physics beyond the Standard Model.

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