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

Laboratory	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	$e^\pm p$	27.5 * 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 2×7 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.

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.

Figure 1 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.

In 1986 the H1 collaboration started with the construction of the detector (see Fig.2) [25] at the electron proton collider HERA at DESY. The highly asymmetric energies of the

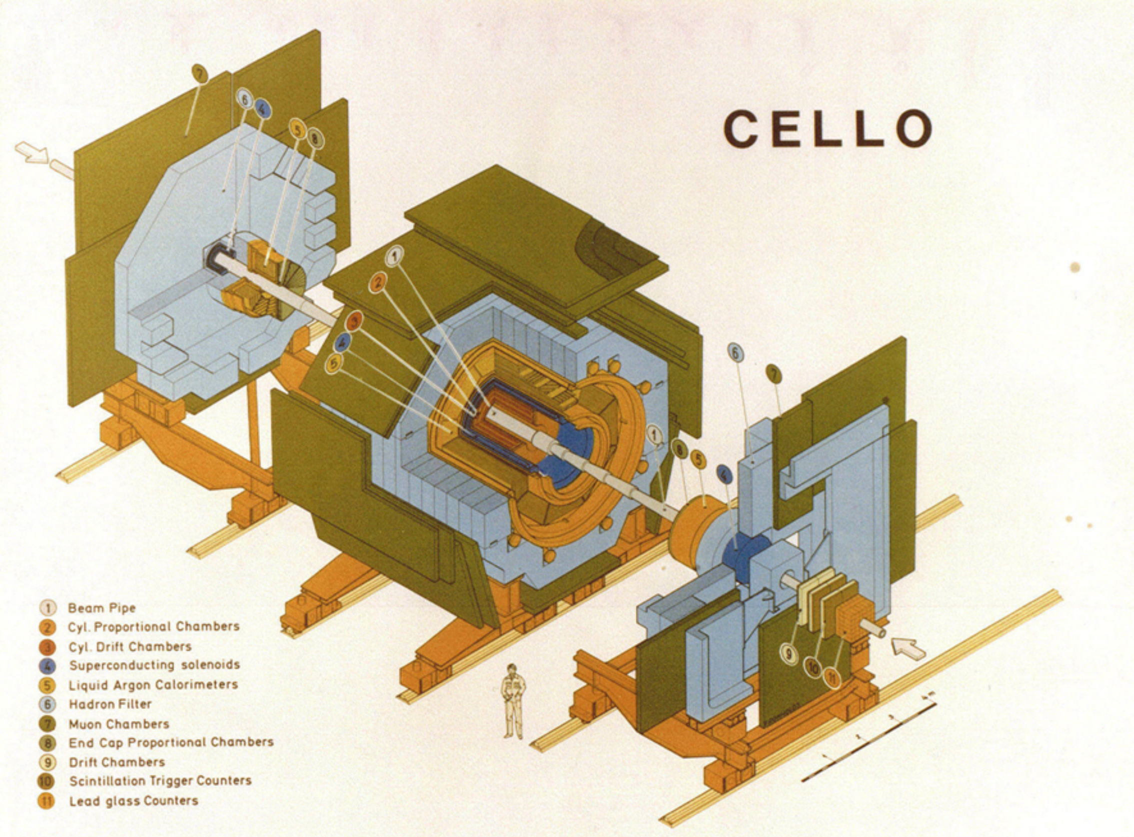

Figure 1: Schematic view of the CELLO detector. Shown are the main detector components: the drift and the proportional chambers of the tracker(2,3), the superconducting magnet(4), the Pb-LAr calorimeter(5), the hadron filter(6) to stop all particles except the muons, and the muon chambers(7).

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.

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

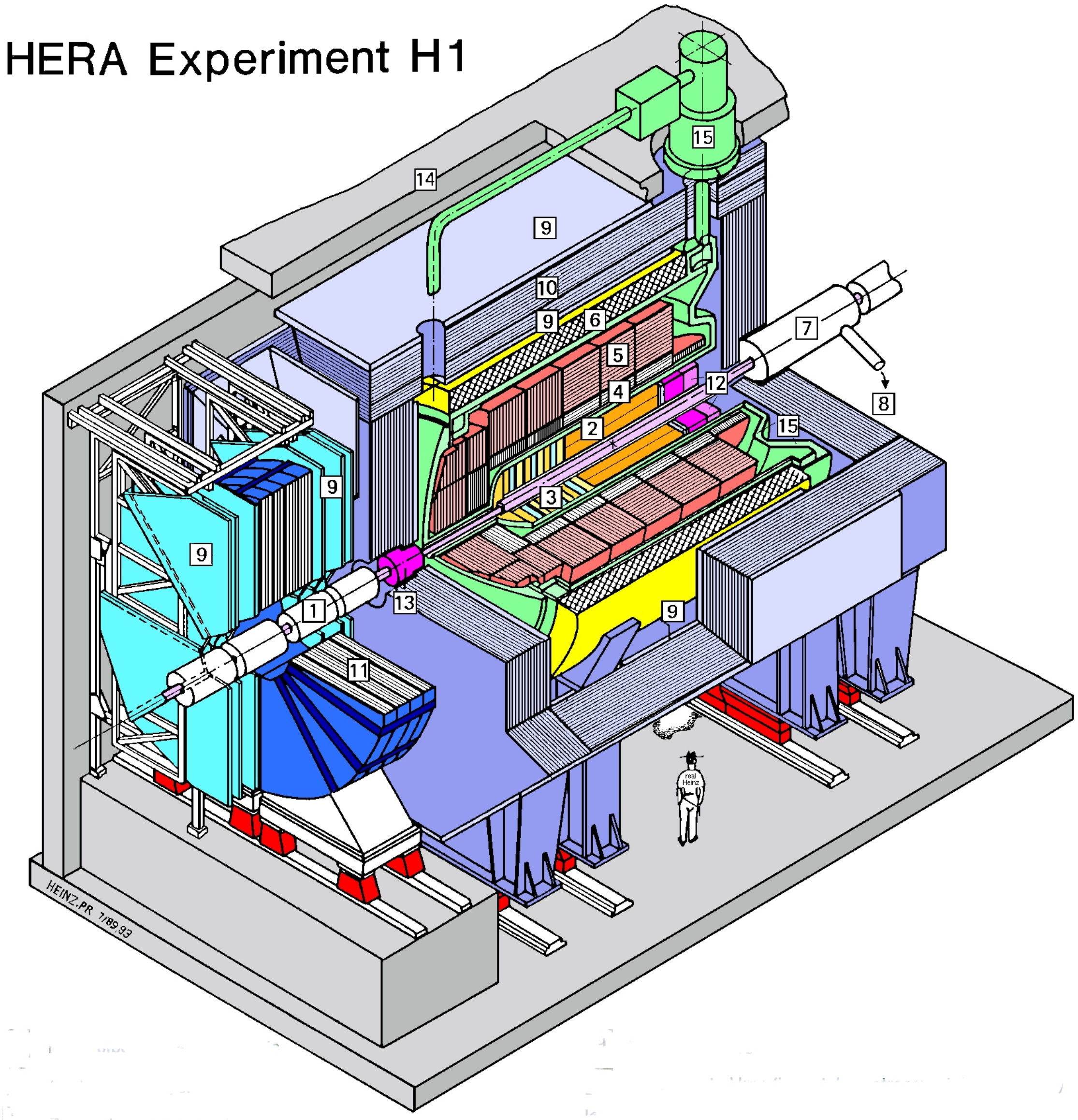

Figure 2: Layout of the H1 detector at HERA. The electromagnetic(4) and hadronic(5) LAr calorimeters are just next to the central tracker(2) and within the superconducting coil(6). The muons are measured in the muon chambers(9).

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 μm. 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.

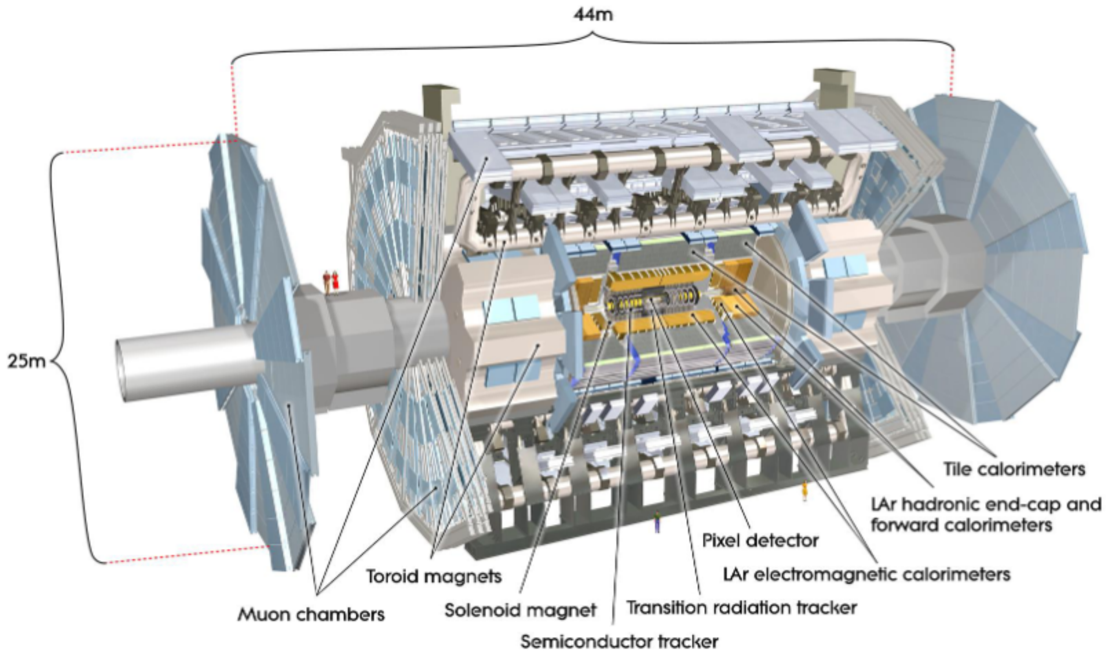

Figure 3: Cutaway view of the ATLAS detector with the central tracking detector (see chapter 2), the calorimeters (see chapter 3), and, surrounding everything else, the central cylindrical (barrel) and the endcap parts of the muon spectrometer with their separate superconducting toroid magnet systems. 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.

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