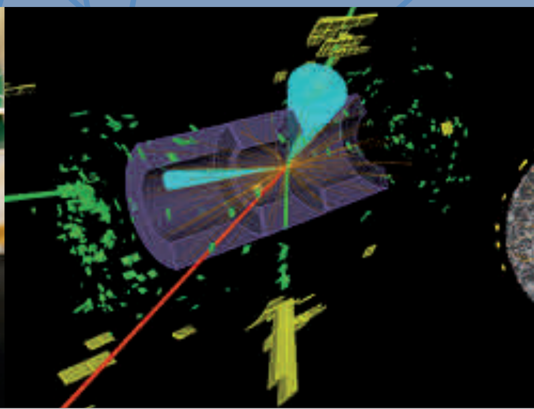




THE HELMHOLTZ ALLIANCE PHYSICS AT THE TERASCALE

A NETWORK TO PUSH THE BOUNDARIES OF KNOWLEDGE

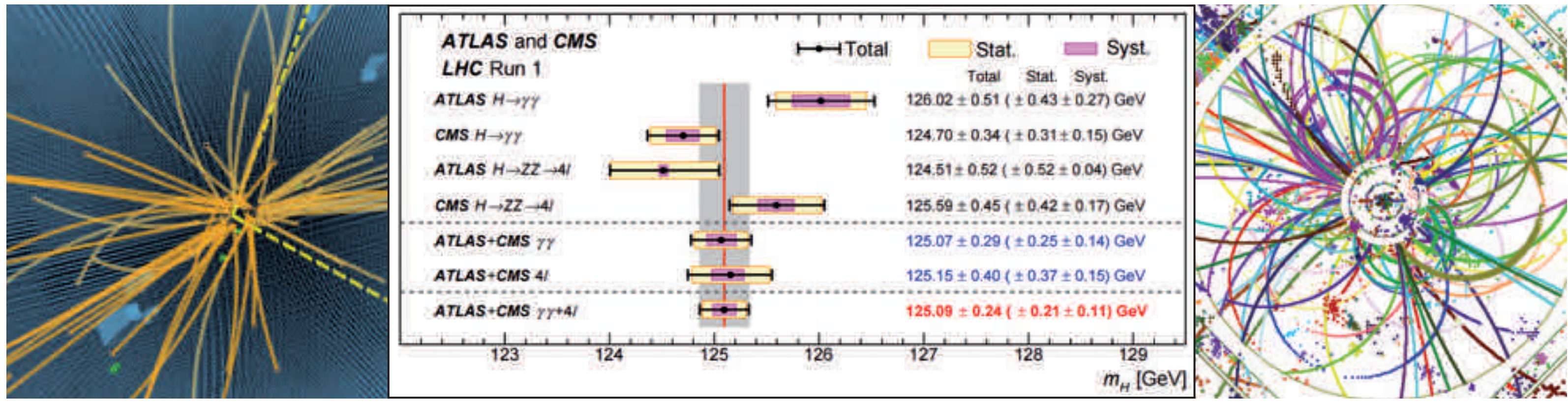
HELMHOLTZ ASSOCIATION

Alliance Physics at the Terascale

CONTENTS

Dear Reader,

Understanding the most fundamental constituents of nature – this is the goal of particle physics. The discovery of the Higgs particle at the Large Hadron Collider at CERN in 2012 has been the latest in a series of spectacular discoveries of the elementary building blocks of nature. Germany has played a very strong role in this endeavour, by participating in international projects like CERN, but also with its strong national programme. For the last eight years, the Helmholtz



Alliance "Physics at the Terascale" has been an integral part of the German particle physics community. The Alliance connects 18 universities, one Max Plack Institute, and two Helmholtz centres in a network of competence and people. The Alliance touches all aspects of particle physics: analysis, detectors, computing, and accelerators.

After eight years, the initial phase of the Alliance has come to an end, and new ways need to be found to continue the work. This is a good opportunity to look back at the past years, to celebrate the achievements of the Alliance, but also to mention its shortcomings. In this brochure the different aspects of work and life in the Alliance will be elaborated. People deeply involved in the Alliance and people watching us from the outside have contributed their views.

The Alliance could not have been successful without the many people who worked tirelessly for its goals. Instead of giving a very long list of names, we would particularly like to mention Rolf-Dieter Heuer, Peter Mättig and Ian Brock, who formed the first management team and were instrumental in making the Alliance the successful instrument it is today.

Ties Behnke and Klaus Desch, Scientific Coordinators of the Helmholtz Alliance "Physics at the Terascale"

Dear Readers,

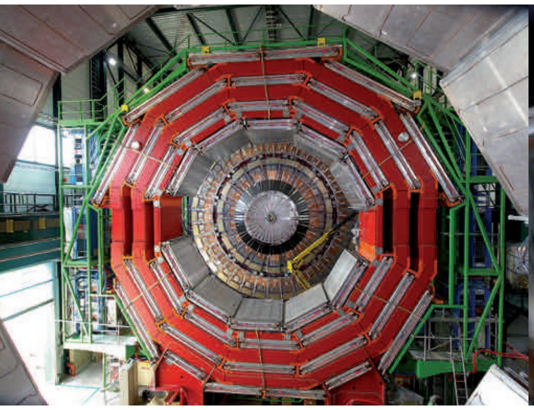
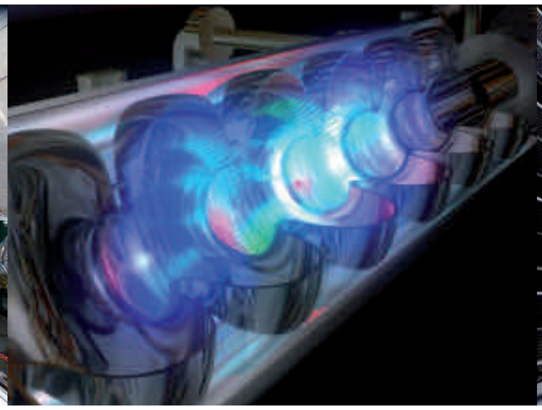
When, in spring 2007, the Senate of the Helmholtz Association of German Research Centres approved the proposal for the Helmholtz Alliance "Physics at the Terascale" and provided €26 million in funding for it from the President's Initiative and Networking Fund, no one knew just how successful the Helmholtz Alliance concept would be.
Admittedly, the selection committee responsible for Alliance requests was unanimous in its enthusiasm for the proposal, but the project required an unusually large amount of funding and more cooperation partners than any other projects previously financed by the Initiative and Networking Fund. The "Physics at the Terascale" Alliance was therefore a sort of model for a forward-looking, long-term network of expertise on a grand scale.

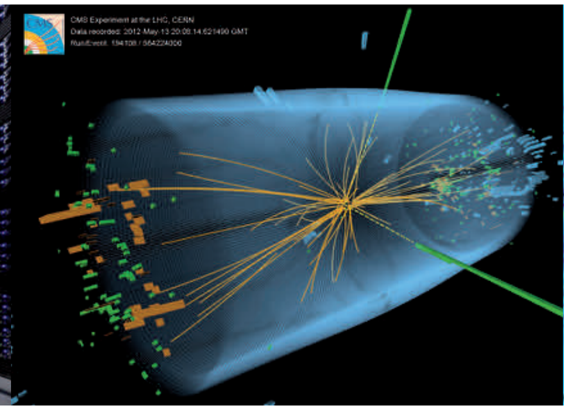
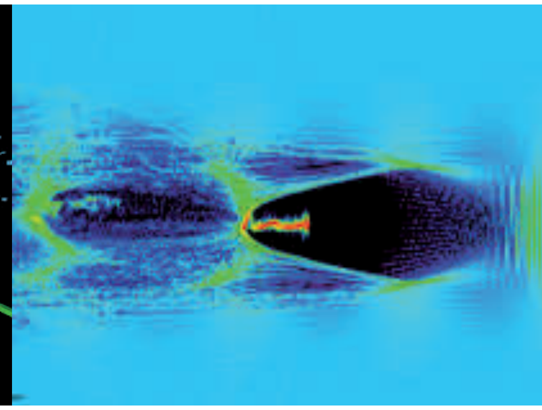
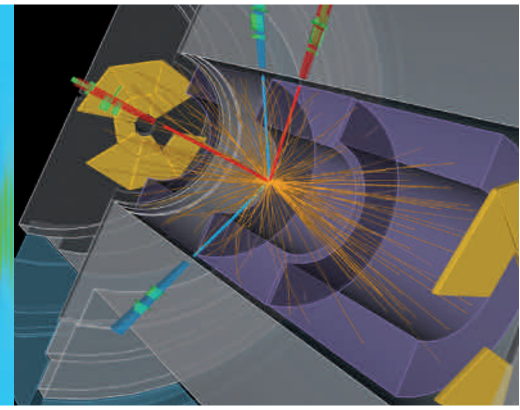
Since then, the Helmholtz Alliances in general and the "Physics at the Terascale" Alliance in particular have proved to be extremely successful, as the numerous publications, conference presentations and workshops that have emerged from the "Terascale Alliance" attest. The success and high standards of the Alliance are also recognised by the international experts involved in the midterm review. With this Alliance, a model for strategic partnerships with universities and other institutions has been established, thereby generating synergies and making a tangible contribution to the dynamic and sustainable development of a fundamental part of the German research system.

Together, the 15 Helmholtz Alliances and five Energy Alliances form one of the key instruments required to achieve the Helmholtz Association's strategic goals in terms of networking, strategic partnerships and the promotion of young researchers. Over the years, they have become the Initiative and Networking Fund's top funding priority and have received more than €230 million. Thanks to the Helmholtz Alliances, new scientific topics can be addressed quickly and followed up closely with financial resources, making a substantial contribution to accomplishing the Helmholtz Association's mission and supporting the Helmholtz Association's mid to long-term programme-oriented funding. In the process, the Helmholtz Association is also fulfilling its obligations under the Joint Initiative for Research and Innovation, which include strengthening the networking within the research system and making it more dynamic.

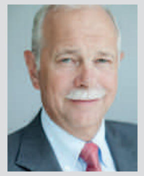
The goal of the Helmholtz Alliances is, and will remain, to become integrated into a research programme with a view to following up the Alliances' respective subject areas in a meaningful way after the funding provided by the Initiative and Networking Fund comes to an end. Given the Alliances' great success in the Matter research area in general – the "Physics at the Terascale" Alliance is joined by the ExtreMe Matter Institute (EMMI) Alliance of hadron and nuclear physicists and the Helmholtz Alliance for Astroparticle Physics (HAP) – and that of the "Physics at the Terascale" Alliance in particular, the Helmholtz Senate Commission and I strongly encouraged all the parties involved to continue and elaborate the proposal for bringing the three Alliances together in a comprehensive initiative that includes the research programmes "Matter and the Universe" and "Matter and Technologies".

I would like to congratulate all those who contributed to the great success of the "Physics at the Terascale" Helmholtz Alliance, including the more than a dozen Helmholtz Young Investigators Groups that played a major role. At the Alliance's inaugural ceremony in 2007, Rolf-Dieter Heuer, then research director for particle physics at the DESY research centre, opened his rousing speech with the words: "Isn't that great?" With hindsight, I can now answer with a clear "Yes, it certainly is!"

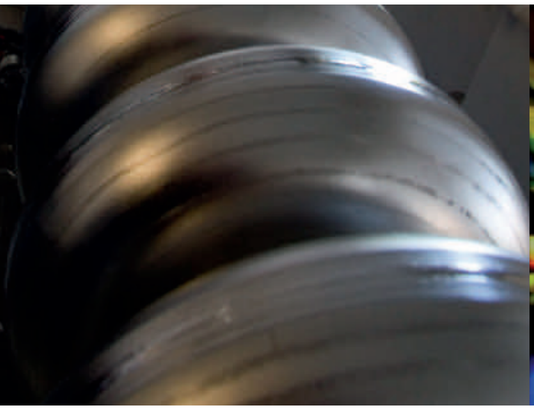




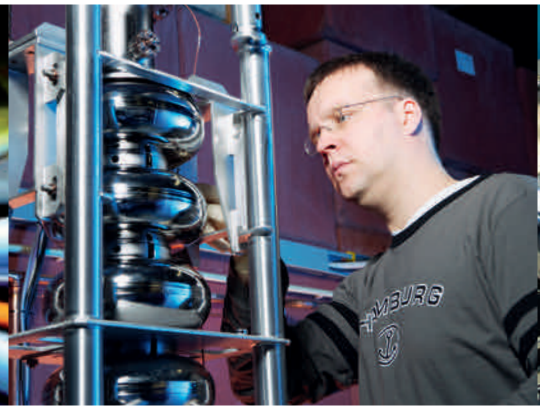
Prof. Jürgen Mlynek has been President of the Helmholtz Association since 2005.

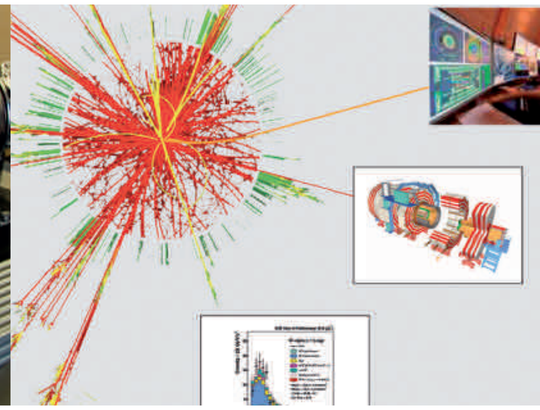


INTRODUCTION

Physics at the Terascale








The year 2007 marked a turning point in the history of particle physics in Germany. With the shutdown of HERA in July, after nearly 15 years of operation, Germany no longer operated an accelerator for particle physics. 2007 also was the year in which the Helmholtz Association announced a new instrument, the “Alliances”, designed to inject new ideas and new structures into the scientific landscape in Germany.

The particle physics community in Germany, lead at this time by Peter Mättig in his role as the chairman of KET, from the University of Wuppertal, and Rolf-Dieter Heuer from DESY, took on the challenge and formulated a broad and ambitious vision – a vision of a coherent community of particle physicists in Germany, bringing together all players, universities, Helmholtz Association, and Max Planck society, united in the goal to make possible a scientific endeavor at the highest international standard in the pursuit of some of the most fundamental questions mankind is asking. The new tool of the Helmholtz Alliance offered the chance to move beyond “Sunday speeches” and actually give substance to this plan. In the course of half a year, it was possible to convince universities and research centers to ear-mark a total of 28 positions, some of them newly created, some early openings of positions, as tenured positions in the field in Germany. Funding for these positions was part of the Alliance proposal, at least for the first 5 years, which was submitted to the Helmholtz association early in 2007, and which was approved later in 2007.

The Alliance was designed to bring together all groups which work in particle physics at the energy frontier in Germany. It should help to restructure the community to react to the new situation with no active accelerator in Germany, and it should help to ensure a pole position for Germany in the – at that time eagerly awaited – new era of physics at the large hadron collider at CERN.

The Alliance was built around four topical pillars, and a number of key actions. The pillars were analysis, computing, detectors and accelerators. Tenured positions placed strategically both in terms of scientific orientation, and location, played a central role. Common actions were the counterpart, which were used to build up the network and create a German-wide community of particle physics.

Networking was done through numerous actions of the Analysis Center, a group of people located at DESY who organised seminars, schools, workshops and other events, accessible to all members of the Alliance. Networking was also achieved by the installation of four coordination groups for analysis, detectors, computing and accelerators. In these groups – or “Project Boards” – experts from the different Alliance member

> “The Terascale Alliance employes a multitude of measures to boost particle physics in Germany”

institutes met and discussed how to shape the respective fields, how to initiate common activities, and how to build a community. And, last but not least, networking was achieved through the installation of a central management structure, with members from universities and research centers who met regularly, discussed issues relevant to the Alliance, and were able to adjust goals and methods to changing demands.

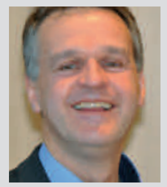
Each year members of the Alliance came together for the yearly alliance meeting. This annual meeting became a fix-point in the yearly scientific schedule, usually organised shortly before Christmas. The meeting offered a review of the field at large, but also of the German role in the field.

The first five years of the Alliance were supported with very generous funds from the Helmholtz Association. Roughly five million Euros per year were available and were distributed strategically among all partners. These Helmholtz funds were backed by roughly twice the sum committed by the partners to Alliance-related topics. Since 2013, funding from Helmholtz has been reduced and finally stopped altogether, at the end of 2014. However, the Alliance continues on, now funded from DESY and its partners from their own funds.

In this report we try to take stock of the last eight years. What has happened, what has been the role of the Alliance, what have been the highlights during this very exciting time? But we also look forward – where will we be in another 10 years?

The instrument of the Alliance has proven to be extremely powerful and well-suited to our field. It has shaped the community over the past years; it has helped to shape a whole generation of particle physicists in Germany, and it will continue to do so in the future.

Ties Behnke (DESY) and **Klaus Desch** (U Bonn) are the current Scientific Coordinators of the Terascale Alliance. They succeeded Rolf Heuer (then DESY, now CERN) and Peter Mättig (U Wuppertal).

A MODEL FOR NATIONAL COOPERATION AND NETWORKING

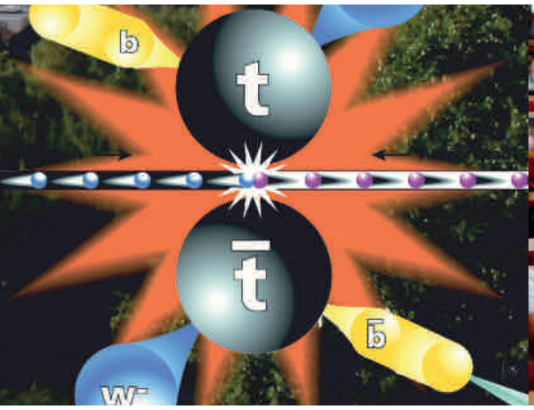
A view on the Terascale from abroad

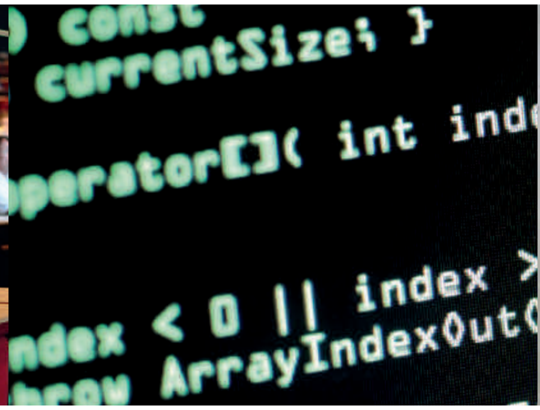
When in early summer 2007 the “Physics at the Terascale” Alliance had been created, the management team formed by the Scientific Coordinators Rolf Heuer and Peter Mättig and the Scientific Manager Ian Brock together with the whole Alliance community of 21 strong partner institutions started to work, with impressive vigour, on filling with life the formidable plan for the Alliance laid down in the Alliance proposal. As a result, already in 2009 the members of the International Advisory Board were convinced “that with the Alliance a structural difficulty within the federal German science system has been overcome to the benefit of 19 universities and 2 Helmholtz centres. This is unique in the German university landscape. Already today one can say that the Alliance is more than the sum of the individual institutes”. Looking back over the past 8 or so years of “Physics at the Terascale”, this has become ever more true.

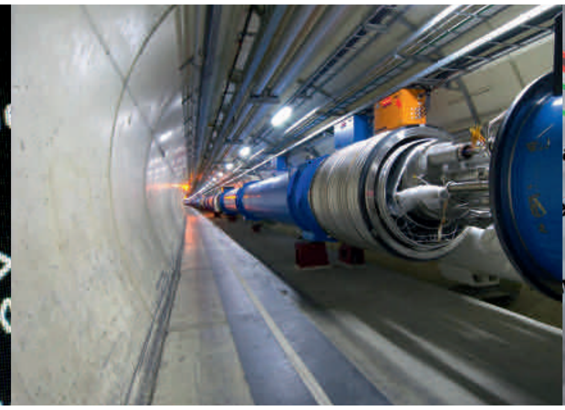
The Alliance has built a network of close communication and collaboration across the German particle physics community. In particular, the groups exploiting the Large Hadron Collider at CERN have been strengthened considerably and their impact deepened. The Alliance has fostered the relationship among the research laboratories DESY, KIT and CERN, the 18 involved university groups, and the MPI for Physics. Also within the Alliance, the exchange of ideas between theorists and experimentalists has reached a new level of efficiency and effectiveness. All in all, the impact of the Alliance has become very visible, e.g. with the highest-quality results at the LHC, in the preparation of which German physicists have often played leading roles, with the massive Alliance support of the German Grid computing efforts, or with the numerous positions created by the Alliance and in not few cases made permanent by one of the Alliance partner institutions. The Alliance has thus strengthened significantly the German contribution to this top-level research.

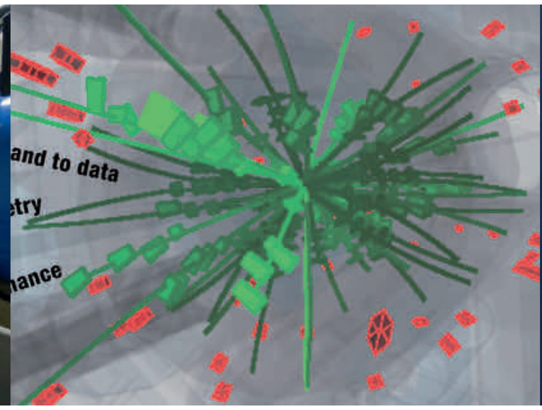
But also other areas of high energy physics profited immensely from the Alliance: The linear collider community was supported as well, and their “Linear Collider Forum” has turned into lively discussion forum, taking place typically twice a year. The Alliance also brought fresh wind to accelerator research at universities, and also with the help of the Alliance plasma-wakefield acceleration was established as a new research direction. The exchange between various groups working in the field of detector development was extremely fruitful, and especially the discussions across the borders of the different collaborations, i.e. between ATLAS and CMS, proved extremely profitably. The annual Detector Workshop organised by the Detector Project Board has become a magnet for detector physicists at all career levels! The importance of the Alliance contributions to the field of grid computing have already mentioned above.

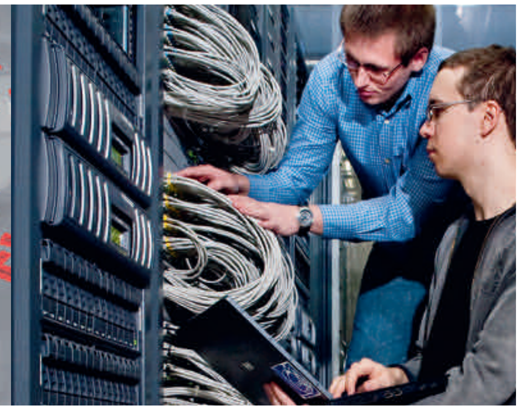
The achievements of the Alliance would not have been possible without the input and the enthusiasm of many young and senior physicists, many of which were supported by Alliance funds.











Especially the creation of several “Young Investigator Groups” in fields as diverse as theory, phenomenology or accelerator development has successfully attracted first-class junior physicists to particle physics and in some cases made it easier for universities to continue to support particle physics.

The maybe most significant impact of the Alliance was the boost given to particle physics education in Germany through the extensive programme of schools and topical workshops with international participation and through the formation of expert centres and various working groups across several universities and experiments. Over the first seven or so years of the Alliance, more than 700 diploma or master students, about 1000 Ph.D. students and 700 post-docs were involved in Terascale-related projects, profiting from the strength of a network of excellence.

> “The achievements of the Alliance would not have been possible without the enthusiasm of many young and senior scientists”

In summary, despite the ending of Helmholtz funding, the scientific programme of the Alliance is meant to be of a long-term nature and is well integrated into high-priority international efforts, let it be the physics exploitation of the LHC or the R&D for an international linear collider. The remarkable and lasting achievements of the Alliance are in science education, coherent research and community building in German particle physics. The Alliance has set up a highly motivating framework for students and it has created an environment offering opportunities to and attracting top class researchers, in particular also those at the beginning of their scientific career. The Alliance has also established a high international profile in particle physics, which attracted research visitors from outside Germany to the Alliance institutions.

Clearly the extra funding provided to the Alliance and its goals by the Helmholtz Association and by the individual partner institutions of pivotal for the initial setup of the Alliance. But of paramount importance was the uniquely positive spirit of German particle physicists and their eager efforts to create a deeper collaboration. Their self-perception as one community made and continues to make the difference!

Dieter Schlatter (CERN) acted as Chair of the International Advisory Board (IAB) of the Terascale Alliance from 2007 to 2012.

Further members of the IAB were (in alphabetic order) **Kors Bos** (Nikhef), **Jim Brau** (U Oregon), **Brian Foster** (then U Oxford), **Peter Jenni** (CERN), **Bernhard Spaan** (TU Dortmund), **James Stirling** (then U Cambridge, now Imperial College London), **Tejinder Virdee** (Imperial College London), **Sakue Yamada** (U Tokyo and KEK). Later, **Neil Geddes** (STFC) joined, while K. Bos, B. Foster and J. Stirling left the IAB.

HOW IT ALL CAME ABOUT

The origins of the Terascale Alliance

It all began in the Committee for Elementary Particle Physics (KET), the coordinating body in particle physics of German universities, DESY and the Max Planck Institute. Towards the end of 2005, KET was contemplating the creation of small networks between the Helmholtz centres, DESY and KIT, the former "Forschungszentrum Karlsruhe", and universities. At about the same time, it was rumoured that Helmholtz intended to create large strategic alliances for core research areas. The idea of joint projects involving Helmholtz and universities gave us hope of overcoming the fragmentation of Germany's research landscape and was discussed at the annual meeting of particle physics in 2005 and at all subsequent KET meetings.

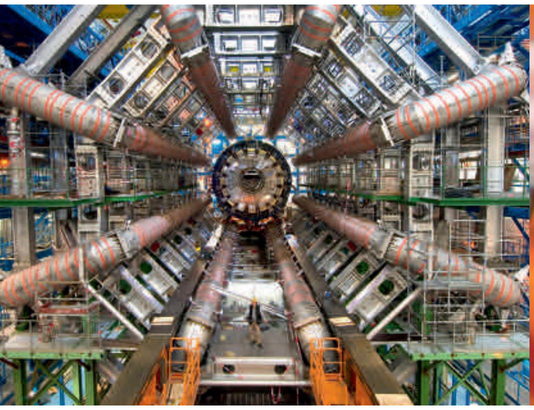
Klaus Desch and Peter Mättig (in close collaboration with Rolf Heuer) were charged with the task of developing a first concept for a large and sustainable Alliance for particle physics. The key idea was to turn the individual strengths of the Helmholtz centres, DESY and FZ Karlsruhe, and of the universities into a collective strength for the whole community, thereby reinforcing the leading role of Germany in the LHC and ILC. The aim of exploring the physics in the TeV range eventually led to name of the future Alliance – "Physics at the Terascale".
The call issued by the Helmholtz Association in July 2006 put forward the goal of treating high-impact research topics in national networks of high international visibility, exactly what we tried to develop. The proposed Alliances across regions on excellent projects complemented the then upcoming and locally organised DFG clusters of excellence.

The Helmholtz call required our project to be worked out within four months. Almost all universities involved in high-energy particle physics enthusiastically embraced the concept of the Terascale Alliance. In the following months, a concept was developed to expand local infrastructures and personnel according to the expertise of the participating institutes, thereby making them usable and profitable for all institutes.

The Terascale Alliance was to rest on three traditional pillars:

- close collaboration between theory and experiment in matters of LHC and ILC physics (data analysis, phenomenology);
- grid computing infrastructure and research, and development of new computing technologies;
- research on and development of new detector technologies.

A fourth pillar was chosen following the need to intensify accelerator research in Germany. The aim was, in particular, to establish accelerator physics more strongly in the university curriculum, using the expertise of DESY in particular.
Many new instruments were introduced to achieve the ambitious goals set in the four projects (which will also be discussed in various places later in this volume). A major new element was the Analysis Centre at DESY that was designed to enhance networking in analysis-related issues, to organise schools, seminars and workshops, and to strengthen topics of general interest, which are less prominently represented at the universities. Another new element was that Alliance positions were opened as tenure track, a procedure that was only recently introduced and not yet well established in Germany.





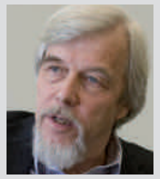

On 6 December 2006, based on an excellent assessment of our draft proposal, we were invited, together with three other consortia out of about 20 who had applied, to hand in a full funding proposal for a Helmholtz Alliance "Physics at the Terascale". On 18 December 35 university and DESY/ KIT representatives met in Frankfurt to decide on further steps. In the ensuing two months, about 25 colleagues contributed significantly to the writing of the proposal. In the course of these two months, binding agreements were provided by all contributing institutes, pledging infrastructure and committing to continued funding for a certain number of personnel hired on tenure-track positions. In fact, the Alliance managed to secure more than 20 permanent scientist and engineer positions for Terascale physics.

Two months later, at the next meeting in Hamburg, a detailed cost plan was developed, and the central elements of Alliance governance were decided upon. The final proposal for "Physics at the Terascale" was handed in to Helmholtz on 28 February 2007. The decisive meeting of the Helmholtz Association took place on 25 April 2007 in Berlin, and we had the opportunity to present our concept to an international review committee. In the following discussion between the committee and the ten selected representatives of our community, the broad involvement of the whole German particle physics community was stressed again and again.

We left with a feeling that – after some discussion stressing the broad scientific horizon of the Alliance – we did a very good job. Nevertheless, we were afraid that the other three, more application-oriented proposals might have better suited the ideas of the review committee. But our fears were unfounded and on 3 June a positive committee recommendation was communicated to us. This was confirmed by Helmholtz on 15 June. In fact only two proposals were finally funded, and our Terascale Alliance was the only one to receive the maximum support of 25 million € for five years.

The Alliance structures were then filled with life in a remarkably short time. Just ten days after the Helmholtz decision, all institute representatives met again in Frankfurt to decide upon the criteria for filling the Alliance's management positions. On 2 July, the constituting meeting of the Alliance took place in Berlin in the presence of Jürgen Mlynek, president of the Helmholtz Association. Mlynek praised our Alliance as a model for collaboration between Helmholtz centres and universities to form beacons of science in Germany. Margaret Wintermantel, president of the HRK (German Rectors' Conference), also stressed this point. Our concept raised international interest, as is documented in various articles in several journals.

The scientific work within the Alliance started immediately at the Berlin meeting. All committees were quickly staffed, positions were announced and filled, and infrastructure was put in place. Work began, as did a very efficient and highly successful collaboration of about 1000 physicists. A network was formed that uses the complementary strengths of universities and Helmholtz centres to substantially increase our influence and impact in research at the LHC and the future ILC. This network is alive and kicking today, and we are looking forward to future developments in "Physics at the Terascale".




Rolf Heuer (then DESY, now CERN) and **Peter Mättig** (U Wuppertal) were the first Scientific Coordinators of the Terascale Alliance. They can be regarded as founding fathers of the Alliance. They were followed in office by Ties Behnke (DESY) and Klaus Desch (U Bonn).

MANAGING THE ALLIANCE

A network of 1000 physicists

Right from the start, the Alliance was humming with activity. Organising a network of about 1000 physicists at 20 different locations is no small job!
There were many new positions to be filled and the structure for making decisions had to be thought out and setup. In addition, the overall Alliance structure with its four pillars (physics analysis, grid computing, detector science and accelerator science, see Fig. 1) and with numerous work packages and activities posed many organisational challenges:

- collaboration and cooperation between the various partners had to be fostered;
- positions had to be filled and responsibles for the various activities to be found;
- the foundations for common infrastructure – like the virtual detector laboratories – needed to be laid;
- and all the odd bits and pieces that are always there also had to be taken care of: reporting, budget, management of the various Alliance bodies ...

The Scientific Managers of the Alliance tackled these tasks by travelling, email, telephoning and meeting! We visited all partners at regular intervals, tried to find out about activities, about potential collaborations, and about problems, and we aimed at weaving an ever-tighter network among all institutes and colleagues. A key activity at the beginning was the filling of the Alliance fellows positions. Boards with one member for each institute that was allocated a fellow position were formed with the Scientific Manager as the chair. This was a first for such positions in Germany and set the style for nearly all appointments in the future. The scientific manager also played a key role in the filling of the YIG positions.

In close collaboration with the project boards, different activities were chosen and carried out for the different research projects: in the case of the Analysis Project (pages 20/21), the setup of the Analysis Centre, of the Virtual Theory Institute seminar series and of several working groups was crucial for achieving the required close collaboration of physicists from different institutes, from different experiments, and from experiment and theory. The main task in the Grid Project (pages 26/27) – besides numerous small projects (tool development, education, etc.) – was to support the university Tier-2 centres in Aachen, Freiburg, Munich, and Wuppertal (and later also in Göttingen) as crucial parts of the German WLCG contributions and to finance and build up the National Analysis Facility (NAF) at DESY. This structure of Tier-2 centres and NAF contribute significantly to the competitiveness of German analysis efforts and also have an important educational effect.

A central task in the Detector Project (pages 22/23) was the organisation of the virtual detector infrastructure in Heidelberg, Bonn and other places. Using this and other infrastructure the Detector Project conducted many R&D activities that will not the least influence the upcoming LHC upgrades!
The Accelerator Project (pages 30/31), finally, aimed to re-establish accelerator research and education in selected university institutes – and has successfully done so by providing lecture series, by establishing the accelerator school, and by getting Bonn and Wuppertal together with DESY and Hamburg more involved in developments and encouraging their cooperation. In addition, a young investigator group was set up in Hamburg.

Towards the end of the initial Helmholtz funding in 2012, the managers were centrally involved in efforts towards a prolongation of funding, and in discussions about alternative funding solutions. You will read about the MUTlink concept in this volume (pages 14/15), and hopes are that in 2015 we will be able to secure additional new funds for this exciting perspective offered by the new Helmholtz programme structure.

So all in all, plenty to do for the managers! We are confident that the preparation of this brochure will not be the last task for Alliance managers!

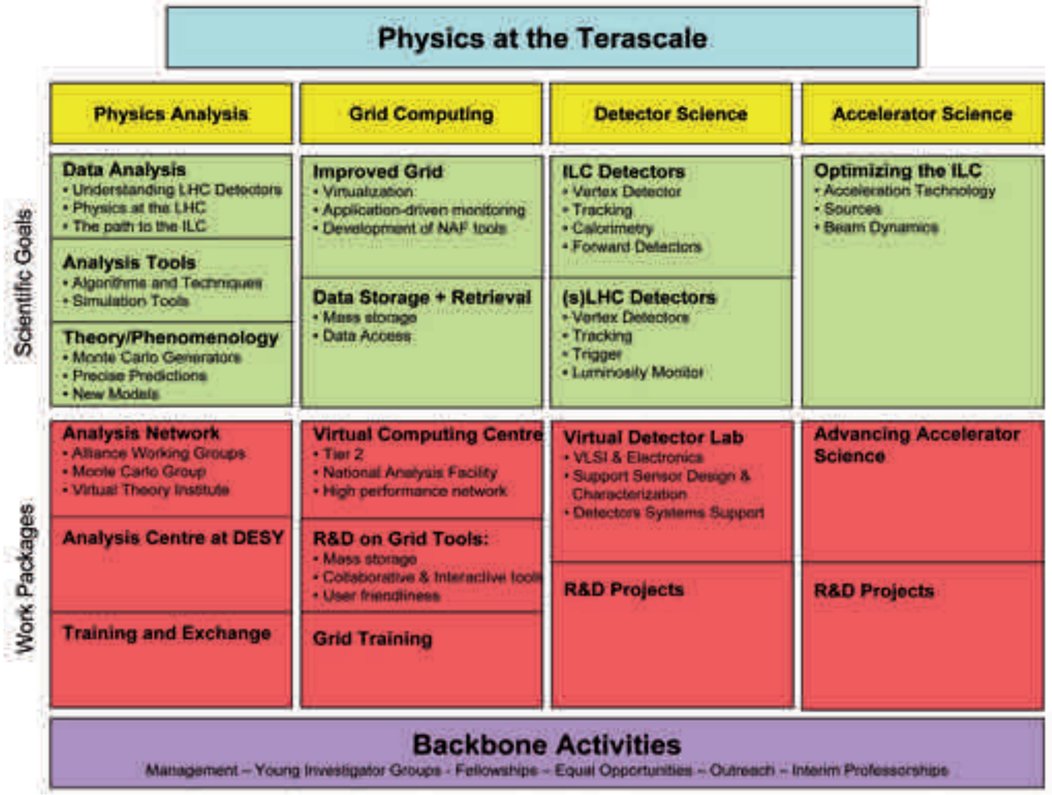
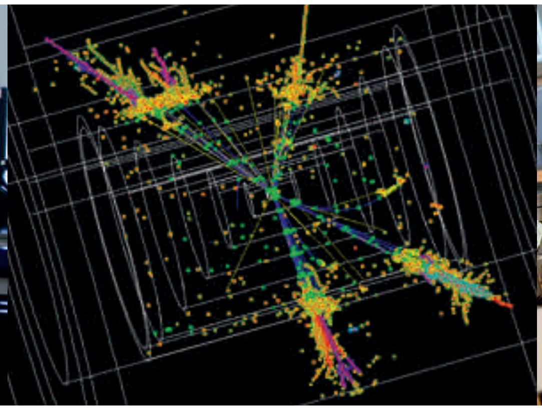
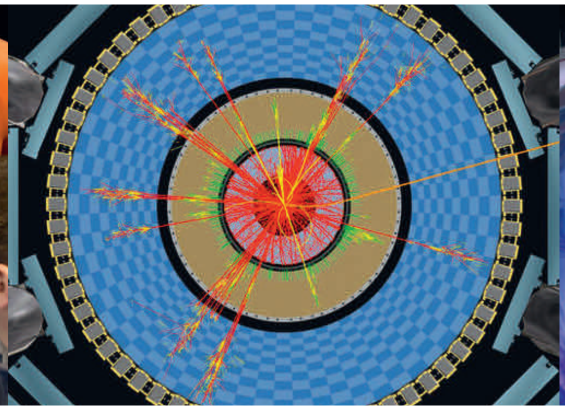
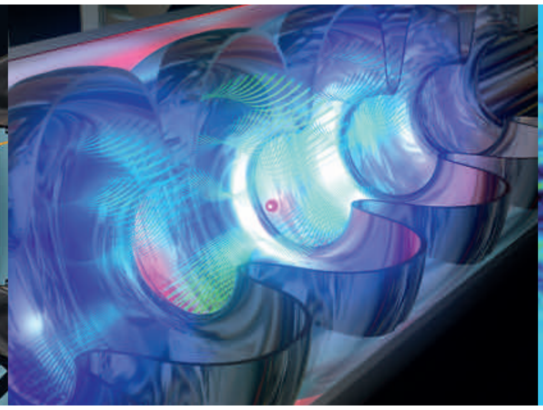
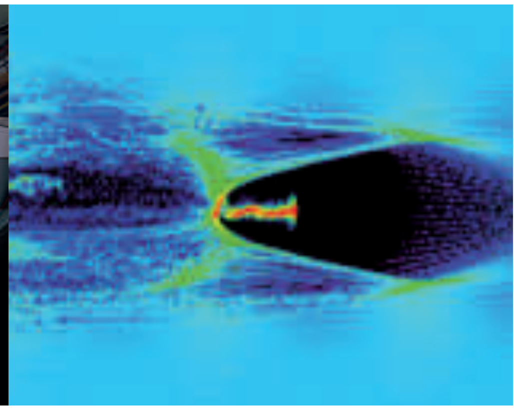


Figure 1: The basic structure of the Alliance with its four pillars.

Ian Brock (U Bonn, left), **Christian Zeitnitz** (U Wuppertal, centre) and **Thomas Schörner-Sadenius** (DESY, right) succeeded each other as Scientific Manager of the Alliance.



MUTLINK – THE ULTIMATE NETWORK

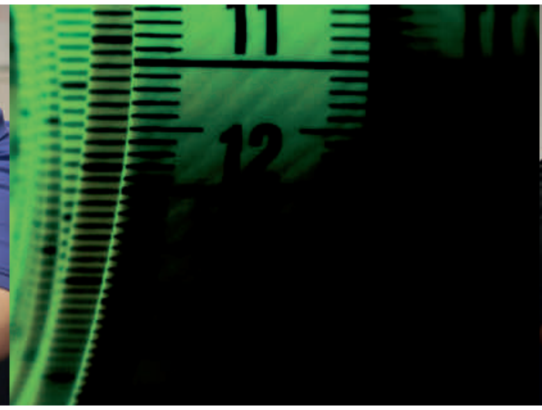
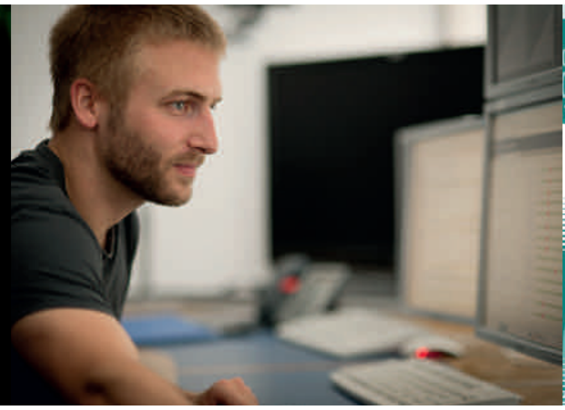
Combining the best of „Matter and the Universe“ and „Matter and Technologies“

Our grand scientific challenge is to understand subatomic physics and the universe at large. That is close to „mission impossible“, but we are ready to take it up. Our targets are the fundamental forces and the smallest particles, the largest structures in the universe, and the most complex phenomena of matter between these two extreme scales.

Helmholtz has made a bold step to reconfigure the well-established research field „Structure of Matter“ into a new arrangement now simply called „Matter“, which comprises three research programmes: „Matter and the Universe“, „Matter and Technologies“, and „From Matter to Materials and Life“. The first programme joins particle physics with astroparticle physics and with nuclear and hadron physics. The second one bundles the more generic cutting-edge research and developments in the fields of detectors and accelerators, and the third one comprises Helmholtz science activitivies with photons, ions and neutrons.

Science networks with own resources have proven to be extremely efficient and effective – the Terascale Alliance has pioneered this enterprise. Two more alliances are active in „Matter and the Universe“, the Helmholtz Alliance for Astroparticle Physics HAP and the Extreme Matter Institute EMMI.

The grand challenge put forward above and the Helmholtz way to address the task lead to a clear conclusion: now we must link Helmholtz centres, research programmes, programme topics and entire communities in German universities and strategic partners all over the world! This approach leads us to conceive a resource-loaded network named MUTLink, the Matter–Universe–Technology network.
Building MUTLink now is necessary, challenging, timely and feasible – thanks to the huge success of Terascale, HAP and EMMI. It is necessary to exploit the different potentials in Helmholtz and at universities. It is also required to advance the connections between the three programme topics to a qualitatively new level now across the communities.
MUTLink is very challenging by itself because it is a very large network. However, it is strongly desired by all members of the anticipated network, and everybody is highly committed to its success. The resources will be used to enable rapid start-up of projects, to support scientists to work intensively on cross-topic subjects, to allow for extensive mobility of people and ideas, and to conduct schools and workshops.
MUTLink at work will be modelled like an international collaboration of peers and is once again a best-practise example of partnership between Helmholtz, universities and other institutions. We do hope that MUTLink can be funded soon.

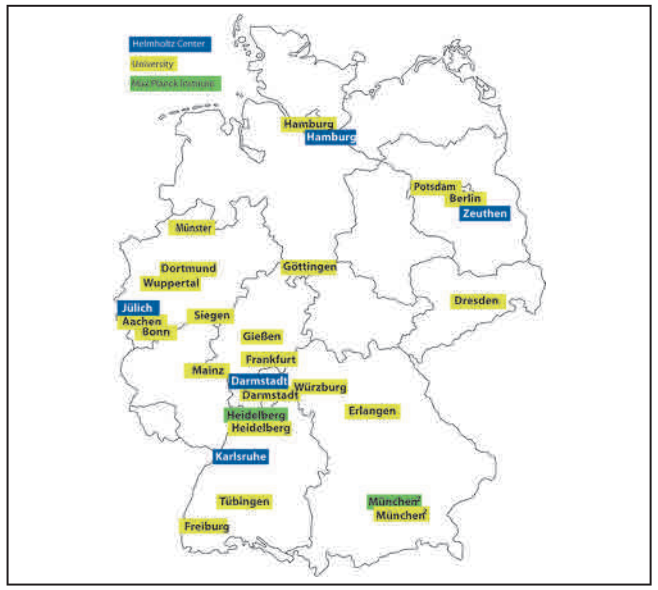


Figure 1: MUTLink partners world-wide and in Germany.

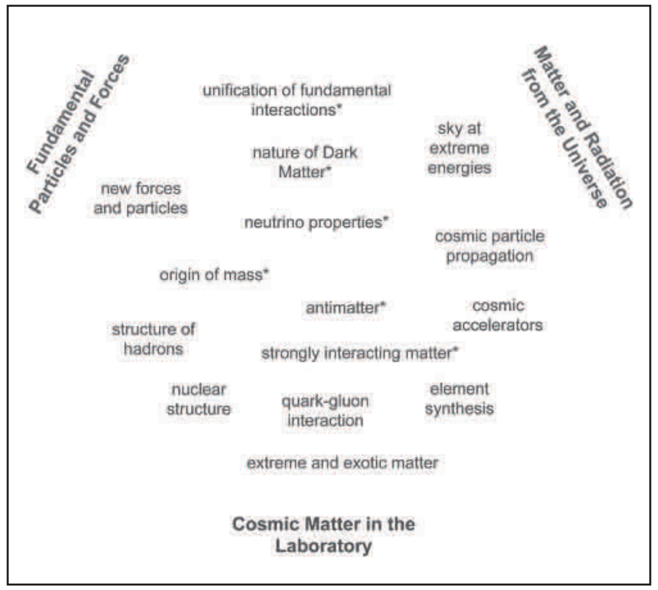


Figure 2: Cross-topic activities between the three programmes topics in „Matter and the Universe“

Johannes Blümer (KIT) is programme coordinator for the Helmholtz programme „Matter and the Universe“ and spokesperson of the Matter-Universe-Technologies network MUTLink.

THE ANALYSIS CENTRE

A Central Forum for Terascale Activities

The Analysis Centre was, according to the proposal, designed to “enhance the analysis activities for the LHC and preparations for the ILC in Germany”. The centre, with its nucleus at DESY, should concentrate expertise on several basic aspects of LHC and ILC analyses and provide key infrastructure to the broader Terascale community. The main tasks can be summarised as:

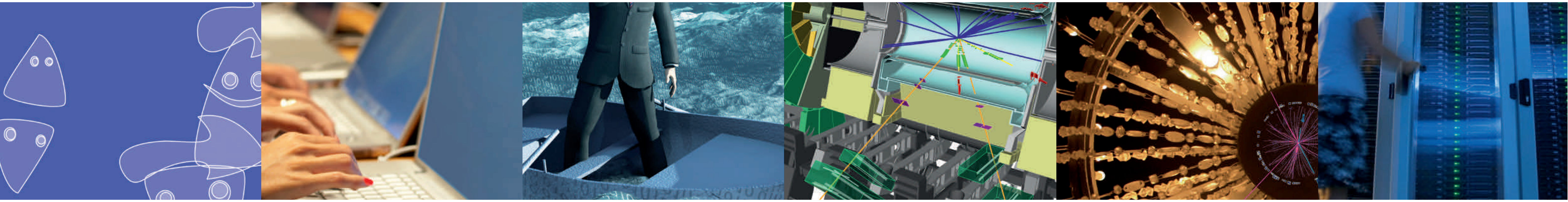
1. organisation of scientific activities on selected topics that are of significant importance for the community;
2. education, training and exchange: organisation of schools, training events and workshops;
3. communication and networking, with the aim of identifying new areas of collaboration and strengthening existing ones.

Two main considerations had led to the idea of the Analysis Center: First, performing analyses in large groups or collaborations like the LHC experiments is a very difficult and complex task. The German groups therefore expected a significant strengthening of their position internationally from pooling their expertise and working together on key questions, even across the boundaries of collaborations and between theory and experiment. Second, some areas – like, for example, Monte Carlo generators and programs – are of central importance to all groups, but are generally difficult to accommodate in an academic setting. In particular, long-term support is hard to obtain for such activities at universities. Here, the Analysis Center as a common institution supported by universities and Helmholtz centres alike could step in and provide central expertise and long-term support.

The Analysis Center was organised around a small number of dedicated and partly tenured personnel, who could focus in particular on the overall organisation of the Analysis Centre and on the physics topics of Monte Carlo (MC) generators, statistics tools, and parton distribution functions (PDFs). In addition, the National Analysis Facility was soon set up as a central infrastructure. Most of these activities are covered in detail elsewhere in this report. Therefore, at this place I will attempt a critical assessment of the Analysis Centre.

The activities of the Analysis Centre had to be organised in an environment characterised by fierce competition between, for example, the experiments, and the wish and the need for cooperation among the different players, because of lack of resources. Thus, the three main topics of the Analysis Centre (MC, statistics tools, PDFs) were chosen because of their relative independence from the large experimental collaborations, and because of their potentially very large impact on the overall progress in the field.

Monte Carlo generators were clearly the area with the strongest Alliance support: several tenured and non-permanent positions were installed. This had a strong impact on the role Germany could play in this area. Basically all relevant Monte Carlo generators were represented with authors within the Alliance. This strong basis was used e.g. for the organisation of Monte Carlo schools and of informal (at least annual) gatherings of all involved scientists. These events and the constant availability of expertise clearly benefitted the field, and numerous specific activities centered around the Alliance personnel surely were scientifically very fruitful.
Not all goals could be reached, though. In some cases, the competition between the experiments ATLAS and CMS, but also between the various MC generator collaborations was



too strong. To mention one example: The provision of MC tunes was mentioned as one of the deliverables of the Analysis Centre. And indeed, Alliance physicists in the Analysis Centre were critically involved in MC tuning procedures in both ATLAS and CMS. In the end, however, no common ATLAS+CMS tune was achieved. Still, individual tunes for the collaborations were prepared with strong participation by the Alliance.

In general, the Alliance could trigger and maintain cooperations and collaboration on different topics, but could not overcome the strong intrinsic separation between different collaborations. Nevertheless, the Alliance left a lasting impression in many areas. Many “Alliance products” were created in the Analysis Centre – tools, methods, papers, codes –, and a very large number of results and tools carry the Alliance stamp and acknowledge the Alliance support. Difficult as the creation and understanding of performance indicators may be, the by far more than 2000 scientific publications with Alliance acknowledgement send a very clear message: The Analysis Centre created a very productive atmosphere and provided the infrastructure and funding to turn this into scientific output!

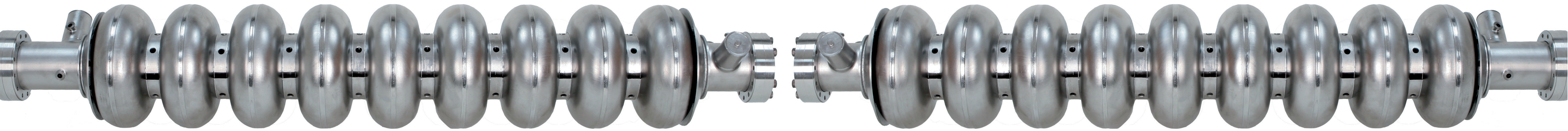
The evaluation of the education and training aspect of the Analysis Centre is much simpler: This is clearly one of the strongest achievements not only in the Analysis Project, but across the whole Terascale Alliance. All in all, since the beginning of the Alliance in 2007, far more than 200 large events have been organised by the Alliance, with an estimated 8000 physicists at all levels of their career participating. There is probably not a single high energy physicist in Germany who has not attended an Alliance event! Some events have set standards and are well established: Probably most Ph.D. students have visited either a statistics or a Monte Carlo school, and events like the School on Advanced Programming Concepts have always attracted small, but highly motivated and highly specialised audiences! This form of centrally organised training events and schools is definitely an asset in the global competition in particle physics; we should eagerly strive to maintain it also for the future! With many Alliance events at which Alliance members could meet and discuss, and with very active Alliance representatives, the optimum opportunities for communication and networking were almost naturally provided. In fact, it is one of the big achievements of the Alliance that all Alliance actors are now more aware of other activities within the Alliance than before!
In summary, the Analysis Centre and the Alliance were very successful in their communication, networking and education tasks. They also provided atmosphere – a certain collaborative spirit – and incentive and often enough funding that enabled significant additional scientific output. They were less successful in directly defining the topics to be worked on – and this is maybe the most important lesson to be learned: People and structures become productive when given the freedom and the means to work on topics they, as a community, are interested in, in a bottom-up approach. The Terascale Alliance in particular, and the Helmholtz Alliances in general, are the ideal instrument for fostering community spirit!

From 2008 to 2014
Thomas Schörner-Sadenius (DESY)
acted as leader of the Analysis Centre of the Terascale Alliance.

[1] The Analysis Centre also hosted numerous smaller activities, which cannot be mentioned here for reasons of space: seminar series, the “Theorist of the Month” programme, travel and working group support, etc.

TERASCALE EVENTS

The Terascale in posters

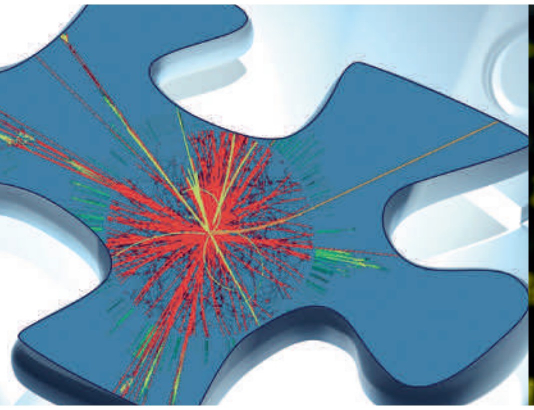


THE TERASCALE ANALYSIS PROJECT

Strengthening physics analysis at the Terascale

The aim of the Analysis Project was to support German groups in their physics analysis activities. Central to the Alliance idea was the fostering of close and intense collaboration between the different groups and communities working on Terascale physics in Germany: the members of the different LHC collaborations, the ILC community, the theory groups, and colleagues from different institutes.

The far-reaching goals of the Analysis Project were – successfully! – tackled mainly by three measures:



- an Analysis Centre, acting as a forum for exchange and the planning and organisation of Alliance events;
- dedicated working groups concentrating on various technical and physical aspects of physics at the LHC and at a future linear collider;
- a Virtual Theory Institute (VTI) organising a series of theory seminars.

In addition, the already existing LHC-D physics working groups were incorporated into the programme.

The Analysis Centre at DESY (see the detailed report on page 16/17) was set up as the central platform for communication and networking in the Analysis Project. It aimed at acting as a hinge between the various players in the field, it tried to provide flow of information and to take up new initiatives, and it planned and organised most of the events in all four Alliance projects – from schools and training events to expert workshops, conferences, and seminar series.

The Analysis Centre also acted as an umbrella for the various working groups – from the four large dedicated analysis groups directly attached to and supported with person-power by the Analysis Centre to the small, focused and short-lived expert group. Examples for results from these groups will be given later in this report!

Three large analysis groups were originally founded – working on Monte Carlo (MC) generators, on parton distribution functions (PDFs), and on statistical tools; a fourth one concentrating on SUSY and BSM parameter fitting was installed later. The topics of these groups were chosen for several reasons: First, the confidentiality required especially by the LHC collaborations for internal, non-published results naturally restricted scientific exchange between the collaborations and also between experimentalists and theorists to the discussion of tools, algorithms theory issues and alike. Second, the topics mentioned were indeed all of great relevance to all experiments and required massive interaction with theorists. And third, there was considerable expertise at DESY, not least stemming from HERA times.

The latter fact allowed DESY physicists – often specifically hired from Alliance funds – to form a nucleus for the working group that could then attract collaborators from other Alliance partner institutes. In the case of the MC group, an additional young investigator group was installed at KIT, and numerous other positions throughout the Alliance were intended to contribute to the work of the analysis groups. The groups are reported upon later in this volume (pages 38ff).
Numerous other working groups were created (mostly) in a bottom-up approach. The condition for a group to be approved by the Alliance and to receive support was that at least two of the four communities ATLAS, CMS, ILC and theory where represented. In most cases, both LHC experiments and theory were present. In case of their approval, the Alliance supported the travel of working group members to workshops and the organisation of working group meetings.

The working groups typically discussed common theoretical issues as well as analysis and reconstruction tools. The groups typically met during the annual Alliance meetings and in many cases also in between. The following working groups were called into existence; they are also reported on later in this volume (pages 54ff):

- The "Central Jet Veto" group studied the selection of vector boson fusion production of Higgs bosons or vector boson scattering.
- The group on "Higgs-Boson Production in Association with Heavy Quarks" studied the connection of Higgs bosons and beauty and top quarks.
- The "M-tautau" group studied the reconstruction of the di-tau mass for resonances like the Higgs, decaying into two tau leptons.
- The group on "Lepton-Flavour Violation at the LHC" studied the relation between neutrino masses and lepton-flavour violation in light of the physics potential of the LHC.
- The "R-Parity Violating SUSY" group studied specific supersymmetric scenarios and their predictions and reconstruction for the LHC.

The LHC-D working groups, finally, were created by the German Committee for Particle Physics (KET) in 2006 to initiate a wider physics discussion in the pre-data taking phase of the LHC. Since the groups fitted well into the goals and the structure of the Alliance, they were incorporated into the Analysis Project. Five working groups exist: Higgs physics, SUSY and BSM, top physics, QCD and electroweak physics, and flavour physics. These groups typically meet for half a day within the annual Alliance meeting and specifically give also young physicists an opportunity to discuss their analyses with an expert audience.

All in all, the Analysis Project succeeded in establishing and strengthening collaborative analysis efforts in Germany - a fact from which we continue to profit!

In the past years, **Klaus Moenig** (DESY) and **Herbi Dreiner** (U Bonn) acted as Chairs of the Analysis Project Board (APB).

Further members of the APB were (in alphabetic order, status of 2014):
M. Erdmann (RWTH Aachen),
S. Gieseke (KIT),
M. Kobel (TU Dresden),
T. Schörner-Sadenius (DESY),
P. Uwer (HU Berlin),
S. Hansmann-Menzemer (U Heidelberg),
G. Weiglein (DESY).

THE TERASCALE DETECTOR PROJECT

Joining forces in research and development of Terascale detectors

Particle reactions at the Terascale can only be observed through sophisticated detector systems. Detector development is thus a prerequisite for the exploration of the Terascale, and it was an integral part of the Alliance from day one on.

Improved detector concepts and technologies have to be developed both for the upgrades of the LHC detectors as well as for other future experimental facilities like the International Linear Collider. The Alliance brought together all German groups active in research and development of detectors for the Terascale, and it stimulated collaboration across experiments and institutions. The established links between the different groups are an important achievement of the Alliance and will last beyond the end of Helmholtz funding.

The Alliance has also funded the creation and improvement of key technological infrastructures that are required for cutting-edge detector development in Germany. Many of these infrastructures would not exist today without the Alliance. These infrastructures (together called Virtual Laboratory for Detector Technologies or VLDT) have been set up at institutes with experienced local groups and have been made available to all members of the Alliance.
In addition, a number of individual projects have been defined and funded by the Alliance in three phases. They focused on topics and infrastructures of broad interest to the community and supported research at an early stage.

A further activity within the Terascale Detector Project was the annual Terascale Detector Workshop (see the box "Terascale Detector Workshops" below). These workshops, which were always exceedingly well received, are attended by many physicists at all level of their career; they will also be continued in the future.
It is impossible to do justice to all these developments in this short report. In the following, we will therefore discuss a few selected examples that illustrate the success of the Alliance in the area of detector development, starting with the virtual detector laboratories on pages 24/25. A few individual detector development projects will be described later in this report (pages 58ff). The full list of virtual laboratories and projects is given in Table 1.

Lutz Feld (RWTH Aachen) is Chair of the Detector Project Board, further members of which are (status end of 2014):
D. Eckstein (DESY), A. Dierlamm (KIT),
A. Frey (U Göttingen), H. Krüger (U Bonn),
H.-C. Schultz-Coulon (U Heidelberg),
F. Sefkow (DESY), S. Tapprogge (U Mainz).






1	**Virtual Laboratory for Detector Technologies**	
1.1	Electronics System Development	Bonn, Heidelberg
1.2	Sensors: Materials, Design and Characterization	Dortmund, Hamburg, Karlsruhe
1.3	Detector Systems: Development, Infrastructure and Testing	Aachen, Bonn, DESY, Freiburg
2	**Detector R&D Projects defined in the Alliance Proposal (2007-2010)**	
2.1	Tracking Detectors for the ILC	Aachen, Bonn, DESY, Mainz, Rostock, Siegen
2.2	Calorimetry at the ILC	DESY, Dresden, Heidelberg, MPI, Wuppertal
2.3	Trigger Developments for the SLHC	Heidelberg, Mainz
2.4	Radiation-Hard Silicon Sensors for the SLHC	Hamburg, Karlsruhe
2.5	Luminosity and Forward Detectors for LHC	HU Berlin, DESY, Gießen
3	**Detector R&D projects (2010-2012)**	
3.1	Irradiation and Characterization of read-out and detector components	Karlsruhe
3.2	A Test Bench for a Fast Data Transmission Line	DESY, Heidelberg, Wuppertal
3.3	Development of Novel Powering Concepts for Tracking Detectors	Aachen
3.4	Ageing and Background Sensitivity of Particle Detectors	Munich
3.5	Virtual SiPM Laboratory	Aachen, DESY, Heidelberg, MPI, Wuppertal
3.6	Bump Bonding for Flip-Chip Development	Heidelberg
4	**Detector R&D project during the extension of the Alliance (2013-2014)**	
4.1	Enabling Technologies for Silicon Microstrip Tracking Detectors at the HL-LHC	Aachen, Berlin, DESY, Freiburg, Hamburg, Karlsruhe

Table 1: Overview of virtual laboratories and projects within the Terascale Detector Project

TERASCALE DETECTOR WORKSHOPS

The Alliance has established a yearly "Terascale Detector Workshop" which aims to cover the broad field of detector developments for experiments at the Terascale, with a focus on the activities of the German groups. This workshop saw eight editions by 2015 and has a typical attendance of 60 to 80 participants. Each year, three topical sessions are selected, for which national and international speakers are invited. In this way it is possible to expose individual topics in the required depth and to cover, over the years, all relevant areas. Selected topics were, for example, "advanced pixel sensors", "radiation damage in silicon detectors", "low-mass design", "calorimetry", "gaseous detectors", "particle flow", and "trigger upgrades". The workshop is traditionally preceded by a two-day school on specific topics like measurement techniques for silicon detectors, FPGA programming, or finite element analysis techniques. These schools consists of lectures and hands-on sessions and are a valuable contribution to the education of students and post-docs. The Terascale Detector Workshop is very well received in the community and appreciated for its combination of broad view, regional focus, and the workshop atmosphere that allows for an informal exchange between the German groups active in detector developments. It is planned to continue this workshop series with the 9th edition in spring 2016 at Freiburg University.

VIRTUAL LABORATORIES FOR DETECTOR TECHNOLOGIES (VLDT)

Common infrastructures for the Terascale community

ELECTRONICS SYSTEM DEVELOPMENT (BONN, HEIDELBERG)

The university groups at Bonn and Heidelberg have a long and very successful record in designing and testing application-specific integrated circuits (ASICs) for high energy physics detector systems. The Alliance played a vital role in preserving and extending the required infrastructures and securing skilled personnel. Key people have been hired on Alliance-funded positions that have later been carried on by the Universities. For the Bonn group, this consolidation was an important step towards the foundation of a new university-funded laboratory for detector research and development.

One of the major achievements of the ASIC design laboratory at Bonn was the joint submission – together with LBNL Berkeley, University of Genoa, CPPM Marseille and NIKHEF - of the new ATLAS Pixel front-end chip FE-I4. In addition to the front-end upgrade, the ATLAS detector control system (DCS) has been redesigned by the Wuppertal group, which has developed a new slow control concept based on custom integrated chips. This design effort was supported by the VLDT at Bonn by providing support to the Wuppertal group in setting up the chip design environment and inviting designers to come to Bonn for a certain period of time to get hands-on training during critical phases of the design flow. Two chips in IBM 130nm technology have been successfully submitted: a pure digital chip with DCS controller and DCS device functionality, and a first prototype with full custom analog circuits for the physical layer of the DCS communication (Fig. 1).

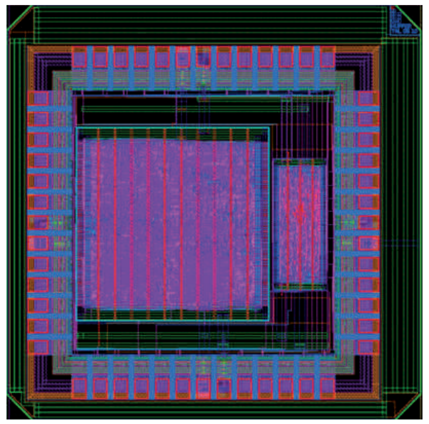
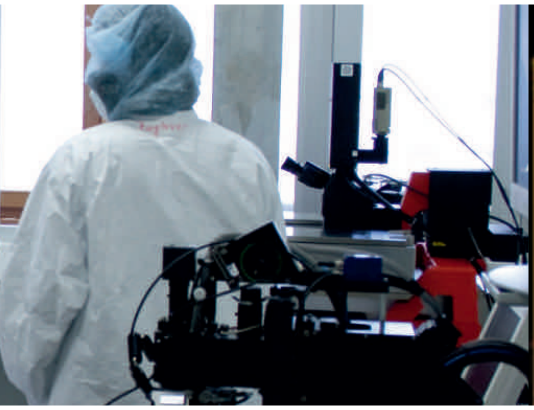


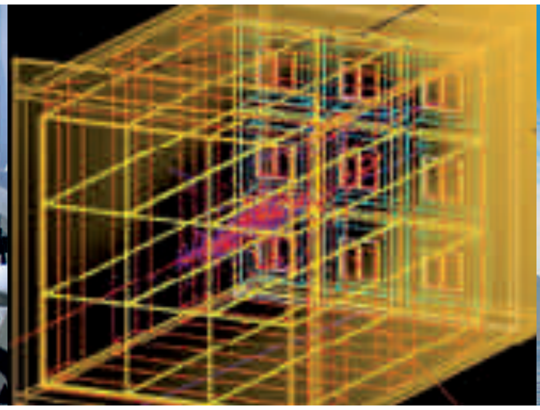
Figure 1: DSC ASIC developed by a group from Wuppertal with support from the Alliance VLDT at Bonn.

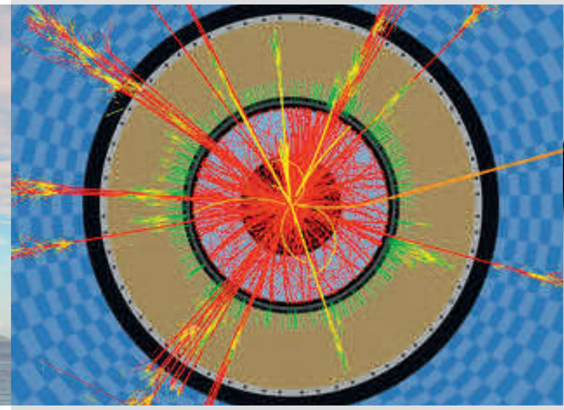
The German participation in the Belle II project was supported through the development of the DHP ASIC. The VLDT Bonn has furthermore contributed to the development of read-out ASICs for time projection chambers (Gossipo, Timepix).

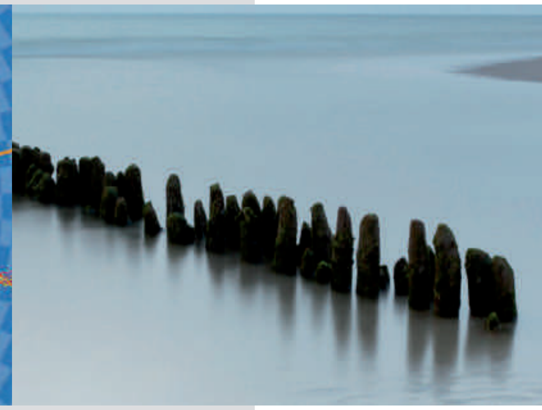
The Heidelberg VLDT is engaged in two core areas of Terascale-related electronics development: the ATLAS Upgrade and the CALICE detector development for the ILC. Both projects make strong use of the new facilities. The lab also served as a support facility for interdisciplinary spin-off projects, in particular projects supported by the Future Emergent Technology (FET) initiative of the European Commission and a project to employ silicon-photomultipliers in PET scanners.

Both groups have offered training opportunities to other Alliance members in form of ASIC design tutorials and an FPGA school.









SENSORS: MATERIALS, DESIGN AND CHARACTERISATION (DORTMUND, HAMBURG, KARLSRUHE)

A highlight in the area of sensor design is a novel m-TCT set-up (multi-channel transient current technique), which has been designed and built with Alliance funding at Hamburg University (Fig. 2). Its main features are 3 lasers with pulse duration below 100 ps, penetration lengths between about 1 µm to centimeters in silicon and focusing down to about 3 µm (rms), and 4 readout channels with 200 ps rise time and 2.5 GHz sampling rate. Since early 2010, the m-TCT set-up is available and has been used for measurements both with and without involvement of the Hamburg University group. The external projects aimed at measurements of the maximum charge containment for DEPFET sensors (MPI Munich), the demonstration of the AGIPD range switching scheme (PSI and DESY), the verification of the input protection of the AGIPD read-out chip (PSI and DESY), and at setting up a data base to verify the simulation of the plasma effect for high X-ray intensities (WIAS Berlin, MPI Munich, Hamburg University).

The m-TCT setup was also used for the experimental study of the performance of segmented silicon sensors for high X-ray intensities and the measurement of the charge collection efficiency in radiation-damaged silicon sensors. Further studies investigated the charge amplification on radiation-damaged epitaxial silicon pad sensors and the impact of surface damage on the charge collection of segmented sensors.

The irradiation and characterisation facilities at Karlsruhe have been opened through the Alliance to all its members. Since the harsh radiation environment in Terascale detectors is one of the main challenges in detector development, the opportunity of a direct and easy access to powerful irradiation facilities (proton irradiation at the cyclotron as well as X-ray irradiation) has been of great importance for many groups.

Figure 2: The multi-channel TCT set-up in Hamburg.

DETECTOR SYSTEMS: DEVELOPMENT, INFRASTRUCTURE AND TESTING (AACHEN, BONN, DESY, FREIBURG)

DESY provides test beams, support for test beam users, and engineering expertise for construction, simulation and integration. The DESY II accelerator provides electron or positron test beams with an energy between 1 GeV and 6 GeV, a small energy spread of about 5%, and intensities of up to 5000 particles per cm^2 and second. In one of the beam areas, a large-bore superconducting magnet with a field of about 1 Tesla has been installed. Ideally suited for tracking studies in a magnetic field, it provides the perfect test bench for lightweight time projection chambers (TPC). More than a dozen groups have utilised the DESY test beam facilities during the lifetime of the Alliance and conducted experiments with calorimeter prototypes, small pixel detectors and TPCs.

A universal gas-mixing apparatus has been developed at RWTH Aachen. The device is able to supply gaseous detectors like TPCs with a precise mixture of up to three different gases. The gas mixing is fully automatised, such that gas properties and detector operation can be studied for the first time in a very systematic way for a large variety of mixtures. Simulations of gas properties can be tested and improved through precise measurements. The gas-mixing unit is mobile and available to be used at other locations.

THE TERASCALE GRID PROJECT

Computing for the (data) masses

Right from the start, Grid computing was an essential project of the Helmholtz Alliance “Physics at the Terascale” – and it constituted a key component for the success of LHC data analysis in Germany. In the Alliance, Grid computing was composed of two strategic components:

- support for Tier-2 computing and the National Analysis Facility (NAF) at DESY (see the article on the following two pages);
- Grid software development projects providing support for the enabling middleware and experiment-specific adaptations to improve analysis tools.

The overwhelming success of the LHC physics programme, culminating in the discovery of a new particle with properties as expected for a Standard Model Higgs boson, was also possible because of the excellent performance of the LHC Computing Grid. On an international level, German Grid sites ranked among the most-used and most-efficient sites in the Worldwide LHC Computing Grid (WLCG). This is also due to the key contributions of the Grid Project of the Terascale Alliance. The Terascale Grid Project has significantly contributed to the German Grid infrastructure for simulation, reconstruction and analysis of LHC data. Major contributions by the Alliance were made in the area of Tier-2 centres at the university sites Aachen, Freiburg, Göttingen, München and Wuppertal, in close collaboration with DESY and the Max-Planck-Institute for physics in Munich. These sites operate Tier-2 centres for ATLAS, CMS and LHCb. KIT in Karlsruhe, the German Tier-1 site, also provides dedicated resources for national users. In the WLCG, this is a very visible contribution at a 15%/10% level for Tier-1/Tier-2 centres.

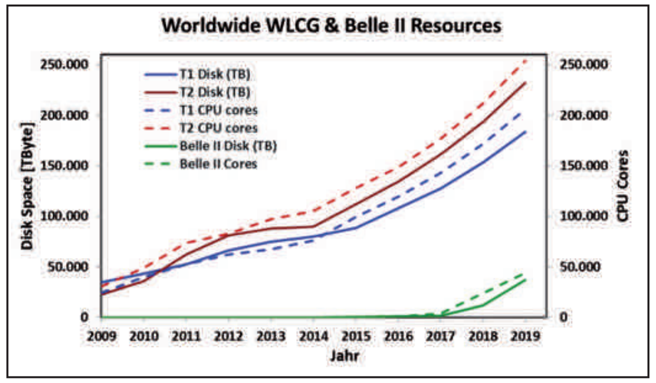


Figure 1: Development of computing resource needs for the WLCG and the Belle II experiment. Germany contributes about 15% of Tier-1, 10% of Tier-2 resources, and 14% for the Belle II experiment.

Tier-2 centres in Germany

The resources in Tier-2 centres at universities presently cover more than 50% of the total Tier-2 capacity available in Germany. Through the years 2007-2012, in addition to covering computing and storage hardware, the Alliance provided funding for personnel, for computing infrastructure, for networking, and for the costs for electric power and cooling. These funds enabled the build-up of the Germany Tier-2 centres, which are further supported through the German Ministry of Education and Research (BMBF). The Tier-2 centres support LHC data analysis for the German scientists, and they contribute to the data production and analysis of the LHC experiments.

The constantly increasing LHC data volumes in Run1 (see Fig. 1) required substantial increases of computing and storage resources at the Tier-2 centres. These increasing requirements were always met, thus allowing for timely and successful analysis of all LHC data. In ATLAS, the German Computing Cloud is the second biggest overall and is operating very reliably. For the CMS experiment, the Aachen and DESY sites are among the most attractive sites for analysis, due to the reliable operation, the large storage and CPU resources provided, and the excellent networking connections.

Grid Development Projects

The Grid development projects of the Alliance, with contributions by all German WLCG sites, stimulated a rich research programme on computing in Germany. It also provided the necessary expertise for coverage of the operational work needed to efficiently operate the Grid infrastructure and to take care of the experiment-specific services. All German centres use the dCache storage system, which is supported by the Alliance support team. Training workshops to prepare and support release changes and new configuration requirements provided support for continuous and smooth operations at all sites. Additional functionality became available through the use of new versions of storage protocols like NFS v4.1, WebDav and xrootd. The “HappyFace” monitoring product, which is developed with significant support from the Alliance, is in operation at most German Tier-2 centres. It allows real-time site monitoring with automatic information acquisition from all sites. Historical information is available for retrieval from a database for performance tuning and correlation studies. HappyFace is also deployed at several non-German CMS Tier-1 sites.

The specific requirements concerning the software environment within the HEP community constrain the choice of resource providers for the outsourcing of computing infrastructure. One way towards more flexibility is virtualisation, and thus the development of virtualisation solutions was supported by the Alliance. The aim is to enable users to perform data analysis on non-HEP-specific computing infrastructures (HPC cluster, cloud).

In the years 2013 and 2014, the interim funding of the Helmholtz Alliance played a crucial role in ensuring Germany‘s position at the forefront of computing developments in high energy physics, specifically for the preparation of the computing infrastructure necessary to cope with the challenges after the restart of the LHC in the 2015 after the upgrade to a centre-of-mass energy of 13 TeV (see figure 1). It was essential to keep the expertise built up by the groups and to enable them to continue their contributions to the successful operation of the Grid infrastructure in Germany. It is only through the universities that the young academics can be acquired that are urgently needed for the future planning, implementation and operation of computing infrastructures in the rapidly changing HEP environment.

Outlook

The requirements for technical data analysis tools for the Tier 2 centres and the NAF are growing strongly, partly because the analysis concepts of the experiments will evolve and become ever more elaborate. The efficient management of large amounts of data and their analysis requires the deployment of further developed storage solutions. New search and access methods for data reduction, strategies for efficient utilisation of fast and reliable networks, and tools for dynamic data management and use of data caching need further development. Also the Grid system software and analysis tools need new technical developments, in various forms, which require thorough studies in order to be successfully used.

In future, the general aspects of computing for HEP data analysis in Germany will be overseen by a coordination board that has emerged from the Terascale Grid Project Board, The board will act as a communication and coordination forum for German computing for HEP.

Matthias Kasemann (DESY)
was the last chair of the Terascale Grid Project Board.

THE NAF AT DESY: THE NATIONAL ANALYSIS FACILITY

Complementing the Grid with additional resources for Terascale analysists

The National Analysis Facility - short: NAF - was designed and initially setup in 2007. The aim was to provide physicists from Terascale institutes participating in LHC and ILC analysis with access to additional dedicated computing resources. DESY, with its two sites in Hamburg and Zeuthen, was supposed to act as a nucleus for the NAF, but extension to other sites in Germany were discussed as an option.

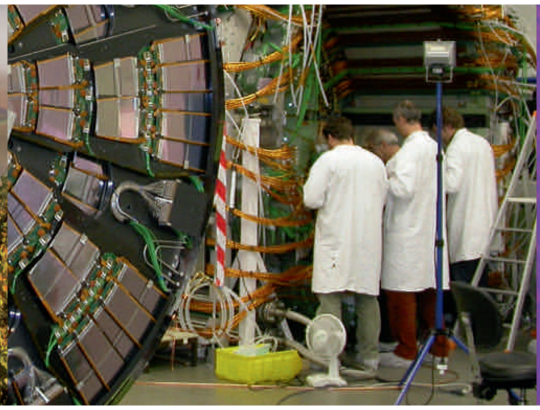
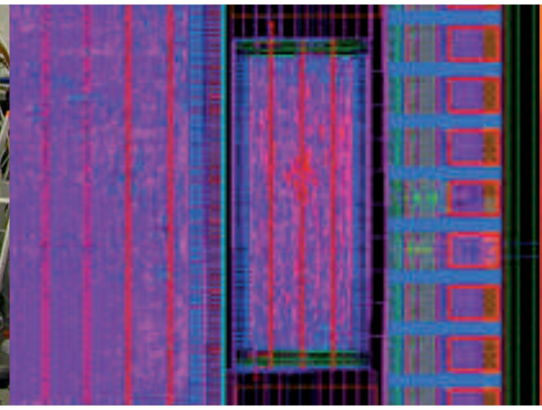
In a first phase, the experiments formulated their requirements to the new facility. It became clear that a dedicated analysis facility should not replace Grid computing and storage, but rather complement it in terms of access and usability. Workshops with experts from the experiments and DESY IT helped to refine the picture, and by end of 2007, first NAF resources went online.

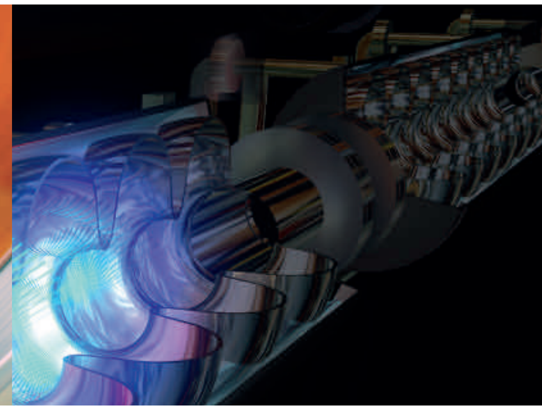
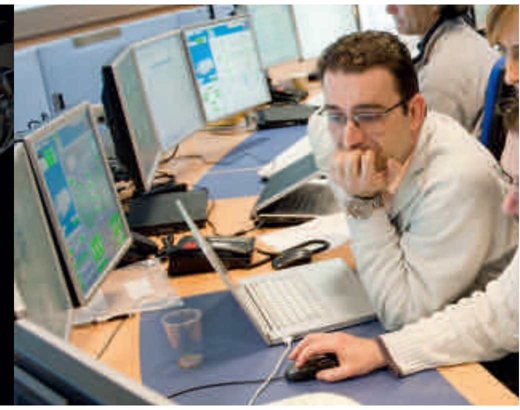
During 2008, all parts of the NAF infrastructure were made available:

- a dedicated user registration with a dedicated AFS cell, relying on Grid certificates as authentication method;
- a small number of work-group servers as login and development machines for each experiment;
- a local batch farm accessible to all NAF users. The Parallel ROOT Facility (PROOF) was offered on the batch platform;
- a fast cluster file system for scratch use (initially Lustre, later SONAS);
- user support on facility level and on the experiment side.

In addition, to strengthen the link between the NAF and Grid facilities at DESY, the DESY dCache storage elements were expanded to offer additional space for datasets outside the official experiment distribution.



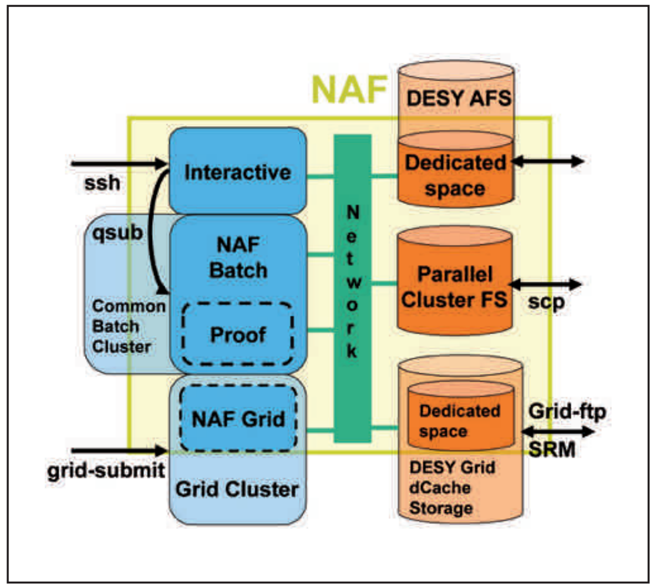


Figure 1: A schematic view of the NAF 2.0 building blocks.

Figure 2: Grid and NAF computers in the DESY computing center.

The NAF grew rather fast in resources, thanks to the Terascale investment. Also usage grew fast, and it grew throughout all participating experiments and institutes.

Even though the NAF was located at DESY, it always was (and still is!) a facility used mostly by non-DESY users. The link between DESY and other Terascale institutes was also strengthened by investments from Hamburg University into resources that were made available to all experiments and institutes.

The NAF was (and continues to be) well used; it hosted many important analyses or significant contributions to them. However, around 2010/2011 it became clear that – in order to adapt to changes of user requirements – the NAF needed a fundamental redesign. This remodelling was planned in 2012 and implemented in 2013 under the project name „NAF 2.0“. Some key aspects were:

- an even stronger focus on data locality and proximity: resources were concentrated at the DESY Hamburg site;
- easier access to resources via normal password authentication;
- increased administration efficiency – NAF resources were integrated into standard DESY management tools and infrastructures;
- new tools, e.g. for graphical login;
- inclusion of Belle II and legacy HERA analysis efforts.

Support for NAF users is jointly provided by DESY IT and experiment experts. Experiment representatives and DESY IT experts also form the NAF Users Committee (NUC), which meets once per month. At least once per year, a larger NAF Users Meeting is organised, usually during the annual Terascale workshop in December.

The NAF was started as a Terascale project and has now grown into an important infrastructure for HEP computing in Germany. DESY is committed to its future and will continue support for the NAF.

Yves Kemp (DESY) actively helped to design, implement and run the NAF as a technical coordinator. As leader of the DESY IT Systems group he still is responsible for the NAF.

THE TERASCALE ACCELERATOR PROJECT

Fostering research in Accelerator Science

TRAINING IN ACCELERATOR SCIENCE (BONN, DESY, DORTMUND, HAMBURG, WUPPERTAL)

The trend to ever larger accelerators for particle physics (HERA, LEP, Tevatron, LHC) led to long lead and running times for new projects and a concentration worldwide of facilities in only a few places, of which the most prominent today is CERN. Several national laboratories diverted the use of their accelerators to other science communities such as photon science users, where availability of the accelerator is of the essence. As a consequence the systematic education and training of accelerator experts at universities slowed down in the first decade of the new millennium and the urgently needed progress in accelerator science for particle physics started to be at risk. When founding the Alliance “Physics at the Terascale” this aspect was well recognised and several German universities agreed to participate in the Accelerator Project, namely Bonn, Hamburg, Wuppertal and later Dortmund – complemented by DESY with the aim of engaging in training young scientists in accelerator science. The goal was to provide rigorous training of conventional accelerator physics and to open research fields that would attract students for an academic career.

ACCELERATOR SCHOOLS

Schools in Hamburg and Dortmund were organised and attracted students from all over Germany to a curriculum that offered basic courses in accelerator optics and technology and discussed the use of these in current or planned accelerators such as the LHC or the ILC and light sources. The lectures were complemented by hands-on exercises in beam optics. The schools also devoted a considerable share to novel acceleration technologies where breakthroughs had recently been made in laser based plasma wakefield acceleration and in reducing the energy spread of the obtained particle bunch. Lecturers came from the participating universities, CERN, DESY and the Max Planck Institute. The one-week courses forged new links between the students and effectively led to a larger acceptance of the accelerator topic as an academic interest.

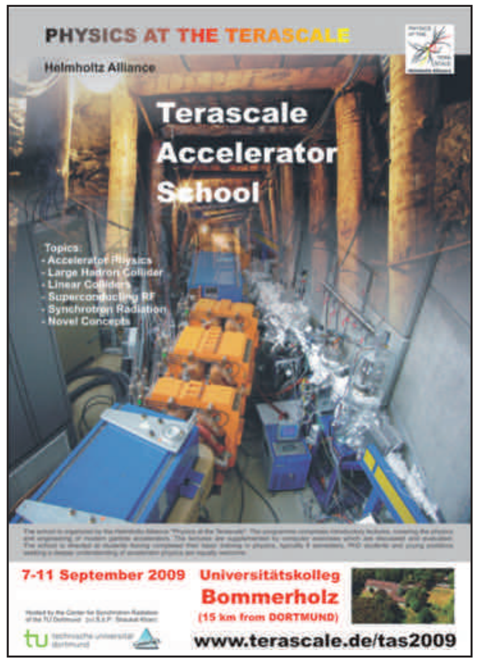
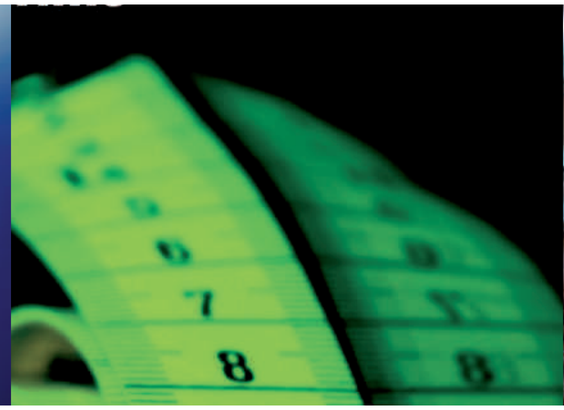


Figure 1: The poster of the second Terascale Accelerator School organised by the Technical University of Dortmund



RESEARCH TOPICS

Two major research topics were identified: superconducting radio-frequency (RF) and plasma wakefield acceleration. The former is the technology for the planned International Linear Collider (ILC) while the latter is an acceleration principle that promises much higher accelerating fields which yet have to be demonstrated in real applications.

The ILC is the e^+e^- collider planned to complement the physics searches of the LHC by virtue of the cleanliness of the initial state. Its approval largely depends on the cost which is dominated by the length of the linear accelerating section and hence by the strength of the accelerating electrical fields. The maximum sustainable field in a superconducting cavity depends on the purity and smoothness of the surface of the niobium superconductor. The construction of the European XFEL gave the opportunity of investigating these cavities in large numbers and to explore the limitation of these cavities following industrial mass production. A key element of investigation was the optical inspection of the cavity surface using sophisticated illumination systems. Several theses were carried out on this topic over the course of time.
Wuppertal provided microscopic feedback on the properties of niobium samples and explored laser cathodes. As an add-on topic, polarisation of the particle beam and its measurement at the ILC was further explored at the ELSA facility in Bonn, where a specific test beam with an associated polarimeter was used.

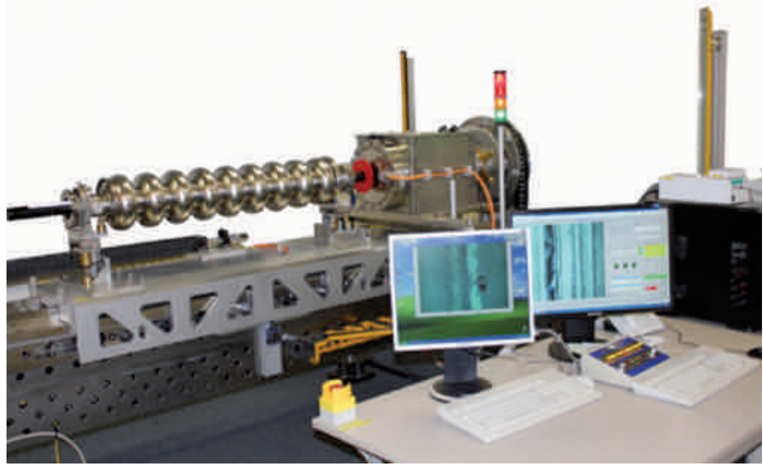


Figure 2: The automated inspection system for the inner surface of superconducting cavities in use at DESY.

The other topical research field, namely plasma wakefield acceleration had seen developments at several universities mostly abroad where progress was largely owed to the rapid development of high-power lasers. Beam-induced plasma wakefield acceleration inherently is restricted to centres which provide the corresponding (conventional) accelerators and safety installations. Hamburg university with its vicinity of DESY was thus ideally poised to host a young investigator position in plasma wakefield acceleration with the goal of harnessing the power of the installed electron accelerator such as FLASH for creation and injection into a plasma. This initiative turned into a highly successful research programme of Hamburg university and DESY which in the meantime has diversified into a sound research field in Hamburg that is well recognised worldwide.

Eckhard Elsen (DESY) was chair of the Accelerator Project Board in the Terascale Alliance and continues to drive accelerator research for particle physics.

BREACHING THE TERASCALE FRONTIER WITH PLASMA WAVES

Plasma acceleration with Terascale incentive

Today's research on physics at the "Terascales" may enable scientific progress on fundamental interactions of particles and fields far beyond Teraelectronvolt (TeV) energies. Those Terascales of importance are Teravolt per meter fields and Terawatt peak powers. Terascale electric fields could allow for the compactification of state-of-the-art accelerator technologies by many orders of magnitude and, thus, a dramatic reduction of future particle physics machines in size and, hopefully, cost. These fields can be generated with a disruptive technology based on charge-density waves in plasmas, so called plasma wakefield accelerators (PWAs), for which Terascale peak power laser technology plays a significant role.

Pushing the boundaries beyond the high-energy physics limits has always been a goal of the Terascale Alliance. Efforts into this strategically important direction, and in particular into plasma-based accelerator technologies within the Alliance started in 2010 with the establishment of my Young Investigator Group (YIG) for Plasma Wakefield Acceleration at Hamburg University. In hindsight, this construction of a university-based research team located within the stimulating environment of the DESY Particle Physics Department, working in close collaboration with machine and photon science experts from all over the DESY campus at the interface of high-energy, accelerator, laser, and relativistic plasma physics created an incubating atmosphere and acted as a scientific growth core. This is exemplified by the number of new research groups on plasma-related topics that were created in Hamburg subsequently. The university installed a new chair for accelerator physics (Prof. Florian Grüner), attracted Humboldt Professor Brian Foster, appointed Junior Professor Bernhard Hidding, and created a Junior Research Group headed by Dr. Andreas Maier.

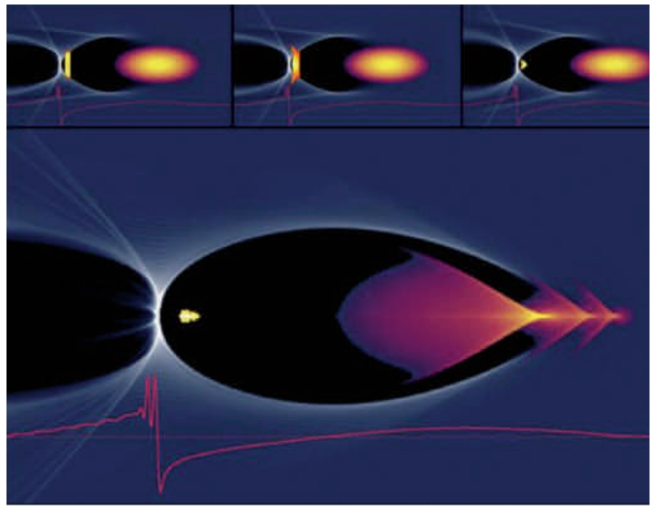


Figure 1: A short, high-energy beam is created by wakefield-induced ionisation injection of electrons from helium into a hydrogen plasma. The evolution of charge density may be seen in the series of four snapshots from a computer simulation at the top.

In 2013, the YIG moved to DESY and was installed as a new research group for plasma-based particle accelerators. At the same time, the DESY Machine department hired a new Leading Scientist, Dr. Ralph Assmann, with a focus on advanced accelerator technologies. In total the number of scientists working on plasma-based particle accelerators in Hamburg grew from 1 in 2010 to more than 70 in 2015, which would not have been possible without the seed that was provided by the Terascale Alliance.

The Hamburg-based PWA activities, condensed in the local LAOLA (Laboratory for Laser- and beam-driven plasma Acceleration) collaboration, are now firmly embedded nationally in the Helmholtz Accelerator Research and Development initiative, and internationally in the European Network for Novel Accelerators. In addition, the Helmholtz Virtual Institute for Plasma Wakefield Acceleration of Highly Relativistic Electrons with FLASH, which was proposed by Terascale members, fosters a collaboration between leading labs in the field such as Lawrence Berkeley, SLAC, John Adams Institute, CERN, and others with a focus on performing groundbreaking plasma accelerator research at FLASH in Hamburg. Besides ample opportunity for collaboration, these networks have allowed to attract significant funding for approved DESY-based PWA experiments (LUX/REGAE, FLASHForward, experimental activities at PITZ in Zeuthen). In addition, there are plans for a dedicated Helmholtz-distributed accelerator research facility ATHENA to be operational in 2022+, for which the center for studies on electron acceleration ATHENAe will be based at DESY.

ULTRAFAST ELECTRON BEAMS

A new technique for the generation of high-quality, ultrafast electron beams has been proposed by members of the Terascale Alliance (see figure 1). Large-amplitude plasma waves of ~100 GV/m field strength may be utilised to selectively ionise Helium atoms, which are doping a fully ionised hydrogen plasma. The electrons freed in this process may bunch in a narrow phase-space volume for the generation of few hundred-attosecond duration beams at GeV energies with few hundred nanometer normalised emittances and kiloampere peak currents. These properties make them highly interesting for applications in photon science.

Reference:
A. Martinez de la Ossa, Phys. Rev. Lett. 111 (2013) 245003.

Jens Osterhoff (DESY) was leader of a Young Investigator Group on plasma wakefield acceleration and is still working on the subject at DESY.

The field of plasma wakefield acceleration is an extremely dynamic one, as is witnessed not only by scientific output but also by the network structures that are established and evolved.
The Helmholtz Alliance "Physics at the Terascale" played a vital role in introducing Germany's premier laboratory for particle acceleration into this strategically relevant scientific domain and linked it to universities that have been active in PWA for more than a decade. This might have been the decisive step in developing current plasma accelerator research from the university level into mature and useable plasma accelerator technology with future applications extending beyond high energy physics into biology, chemistry, medicine, and material science.

If the next after the next particle collider includes plasma technology, it will be in large part a merit of actions taken by the Terascale Alliance.

FACTS AND FIGURES

The Terascale in numbers

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

Number of contributions in INDICO: 5145

5,145

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

Total number of participants in annual meetings: 2335

2,335

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

Approx. number of slides shown during Alliance meetings: 83864

83,864

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

Number of coffee cups drunk during Alliance events: 119753

119,753

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

Kilometres travelled by the managers for Alliance purposes: ~250000

~250,000

THE HELMHOLTZ ALLIAN
Physics at the Tera
Date/Time 20/07/201

Number of Terascale events in INDICO: 670

670

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

IVF	26,665,217.33	EUR
own funds	70,908,635.40	EUR

97,573,852.73 EUR

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

Number of mails sent and received by Alliance management: 179272

179,272

THE HELMHOLTZ ALLI
Physics at the Ter
Date/Time 20/07/2

Number of journal publications: ~2600

~2,600

THE HELMHOLTZ ALLIANCE
Physics at the Terascale
Date/Time 20/07/2015

Number of scientists on Terascale mailing lists: 2435 (double-counting not excluded)

2,435

HE HELMHOLTZ ALLIANCE
hysics at the Terascale
Date/Time 20/07/2015

Alliance babies (estimate): 183

183

THE BACKBONE ACTIVITIES

The Heartbeat of the Alliance

Even before the formal start of the Alliance it had been decided to leave a significant part of the funds unassigned for later allocation. This very wise decision created a large dynamic and had a very positive impact on the overall working of the alliance. This so-called backbone money was used for four main tasks: promotion of young researchers, equal opportunities, knowledge transfer, and interim professorships.

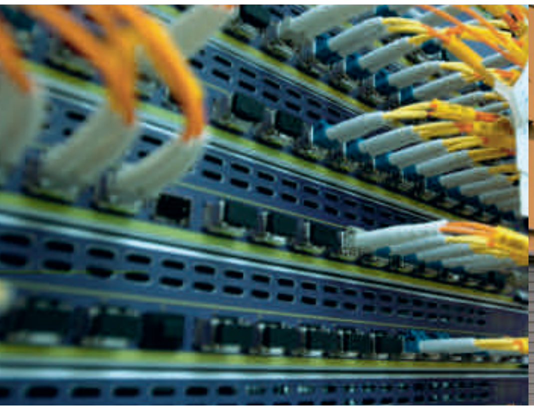
PROMOTION OF YOUNG RESEARCHERS

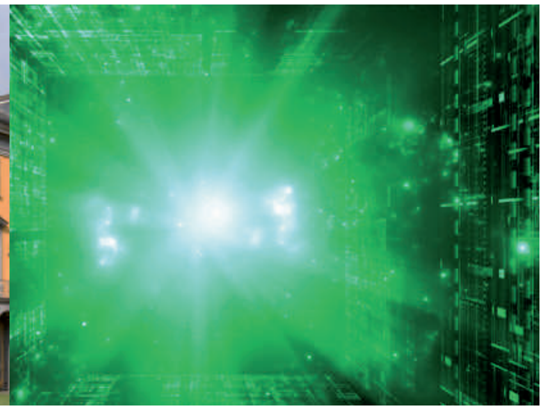
Young researchers were heavily involved in the alliance, and were promoted in a number of ways. The Alliance installed dedicated fellowships, and several young investigator groups (YIGs). Two calls for fellowship positions within the Alliance were issued. Candidates could propose a subject for their work as well as an institute where they wanted to be sited.

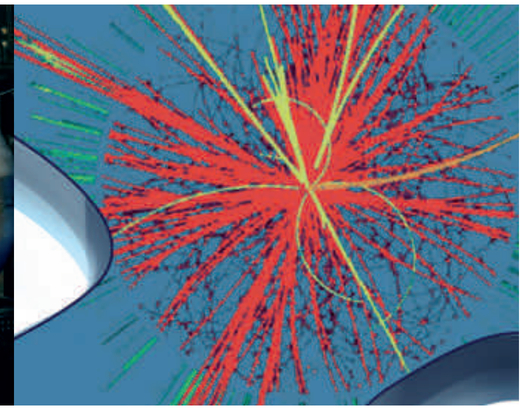
Figure 1: Workshops and schools are a key ingredient of the Alliance.

The selection of the candidates was done by a board with representative from the German community at large – a novum in the field. An additional number of positions could be advertised with tenure track at universitie s and at the Helmholtz centers – also here the Alliance as the whole participated in the selection, but of course the hosting institute had the last word. In total 20 fellowship positions were filled, in addition to topical positions that the Alliance created in its four research topics.

The young investigator groups were modelled after the very successful Helmholtz YIGs. A total budget of 150 kEUR/year was assigned to the selected group leader, which includes his/her salary as well as money for additional group members and for research. The hosting groups typically contributed significant own funds to the group and in all cases a tenure track option. Competition for these positions was fierce – both between institutes, to become selected as a host – as well as for the positions. Through this instrument the Alliance really made a lasting and important impact and shaped in many ways particle physics research in Germany. Even after the formal end of financing of these groups through the Helmholtz association they are strong pillars in continuing to work towards the goals of the Terascale Alliance.







EQUAL OPPORTUNITIES

Equal opportunity measures are implemented at all partner institutes. The alliance added to this and could make a real difference here by focusing its support on dual career measures. Seven temporary positions could be funded for partners of newly appointed Alliance personnel and given to the partner of the person to be hired. Sometimes these positions were in a totally different field of science, but they were instrumental in convincing some very high level people to come to Germany and join the effort. The Alliance also supported a number of smaller measures like support for young families with e.g. childcare at Terascale conferences, etc.

KNOWLEDGE TRANSFER

A large and complex network like the Terascale alliance is a world in itself, and efficient and good knowledge transfer within this network is very important. But it does not stop there – communicating the science outside of the network, to the broader scientific community, but also to the general public, are important and highly relevant tasks. The alliance invested heavily into this through a broad range of measures.

Many Terascale-related workshops were organised. Some started a regular series of topical meetings that go on beyond today even without explicit Alliance support. Examples are the Alliance detector workshops that form a platform for detector R&D discussions within Germany, or the computing workshops.

Earlier in this volume the Alliance Centre has been introduced, where an intense programme of schools and workshops was organised. The financing of these activities was done through the backbone programme of the Alliance. In total more than 50 schools have been organised since July 2007. This programme is being continued today within the Alliance Forum. Knowledge transfer often depends on people.

The Alliance therefore organised a visitor programme, where expert visits to Alliance institutes could be financed. An example of such a programme was the "theoretician of the week" programme at DESY, where highly acclaimed experts were invited to DESY for a week, and were available for discussions, seminars and co-operations to all Alliance partners. But this programme was not limited to DESY, and other institutes used this resource as well. Last but not least, the Alliance invested in outreach activities to the general public. An outreach officer was employed to help in the organisation especially of the LHC related communication effort in Germany. The Alliance also supported the very successful "International Masterclasses", which brought particle physics to high schools in Germany and other countries.

Figure 2: Physics topics supported by backbone activities.

INTERIM PROFESSORSHIPS

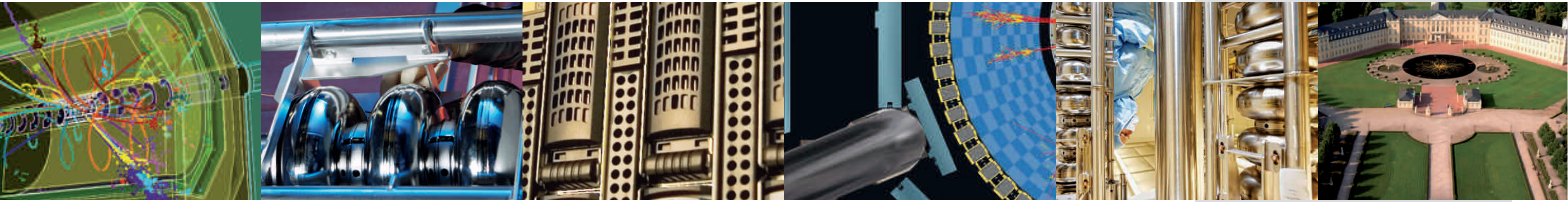
Particle physics is a very international field, which works primarily in the context of large international collaborations. Key positions within these collaborations are very prestigious, but require that the person in charge can dedicate its full time to this position. The Alliance instituted a "teaching buy-out" programme, where replacement people could be financed at a partner institute to allow people – e.g. professors at a university – to take on a full time management position for a limited duration. This was positive in two ways: it liberated university teachers from their teaching duties, allowing them to accept management duties, for example, at CERN, and it gave young people a chance to gain teaching experience. In total 3 of such longer-term buy-outs could be financed.

Karsten Büßer (DESY) is the Administrative Coordinator of the Terascale Alliance.

THE STATISTICS TOOLS ACTIVITIES

Support and education in statistics-related matters

The development of statistics tools and the support and education of Alliance members in statistical matters were central tasks of the Analysis Centre, and for this purpose a statistics tools group was founded as early as 2007. The group, driven and organised by a number of colleagues mostly from DESY, quickly took up a wide range of activities that cannot all be covered here. Two very prominent activities – the organisation of statistics schools and a prominent project supported by the Alliance, the Millepede-II project – will be discussed in somewhat more detail.



Among the other wide-ranging projects of the statistics group were

- support for numerous projects with involvement of Terascale scientists: A number of projects received financial or person-power support through the statistics tools group and the Analysis Centre, for example the BAT (Bayesian Analysis Toolkit) project or the TMVA package;
- meetings of major statistics projects and computer codes, with the aim of cross-fertilisation and exchange;
- informal statistics meetings where everybody could come and ask his / her particular question to experts;
- Analysis Centre seminars on statistics topics; and others.

All in all, the knowledge of statistical procedures and tools has clearly been immensely boosted by the Terascale Alliance and its activities.

STATISTICS SCHOOLS – EDUCATION WITHIN THE ALLIANCE

A highlight of the activities of the statistics tools group of the Terascale Alliance was the series of statistics schools. Typically in each year two schools were held, one introductory and one advanced. The target audiences for the introductory schools were master and Ph.D. students from Alliance or other institutes, and the main aim of these schools was to provide guidance for statistics-related tasks in physics analyses of data from the Large Hadron Collider (LHC) or from other particle physics experiments. The idea was to cover the typical analysis tasks encountered within a Ph.D. thesis, comprising:

- optimal separation of signals and backgrounds in data,
- determining the strength of an interesting signal process or setting an upper limit on it,
- correcting observed signals for detector effects by means of unfolding algorithms and
- determining the final measurement systematic uncertainties of experimental or theoretical origin.

The typical school lasted for four days and comprised lectures and interactive sessions, ranging from simple paper exercises to elaborate computer tutorials.
The advanced schools aimed at more experienced or specialised researchers and were dealing with topics at the forefront of

> The knowledge of statistical procedures has been immensely boosted by the Terascale Alliance.

developments in statistical methods, such as highest-precision combinations of data from different experiments.
The introductory schools were mostly held at DESY while the advanced schools were touring the various Alliance institutes with particular expertise in specific statistical methods. In the period from 2008 to 2014, more than 500 researchers participated in the statistics schools, making them to the largest event series within the Alliance. The sheer amount of participants indicates the success of the schools, which was also reflected by the enthusiastic feedback from the participants.

Olaf Behnke (DESY, left) and **Claus Kleinwort** (DESY, right) together with Gero Flucke (then DESY, now XFEL) and Stefan Schmitt (DESY), were key persons in the Terascale Statistics Tools group and in the organisation of the regular statistics schools.

THE MILLEPEDE-II PROGRAM – AN EXAMPLE OF A TERASCALE-SUPPORTED ACTIVITY

Millepede-II is a software package for solving huge linear equations systems for special applications like the track-based alignment of tracking detectors in high energy physics, originally developed by V. Blobel at Hamburg University. In this specific case, the sum of the normalised distances between the measured and predicted positions in the tracking detectors over all measurements and tracks has to be minimised. The linearisation of the track model (or prediction) leads to a linear equation system for corrections of all alignment and track parameters.
With block matrix algebra this can be reduced to an equation system for the alignment parameters only. With this method, the CMS experiment has simultaneously determined more than 200,000 parameters.

Since some years the statistics tools group of the Analysis Center takes care of the maintenance and development of Millepede-II. This Alliance activity started with the optimisation of memory and CPU time usage of the program by compressing the matrix of the linear equation system and parallelising the code with OpenMP ®. Currently, we are concentrating on improving the (numerical) precision and implementing alternative solution methods. In addition, more cross checks and safety tests are implemented in order to optimise the feedback to the user especially about potential problems with the linear equation system and its solution.

GAMBLING AT THE TERASCALE: MONTE CARLO TOOLS

A prerequisite for precision physics and discoveries

PRECISION MEASUREMENTS NEED TOOLS

Deep insights into nature can only be obtained from the comparison of a measurement with the corresponding theoretical expectation. For a thorough understanding of the very complex measurements performed at the LHC, these theoretical expectations require both a of the underlying physics processes in the proton-proton collision and a simulation of the detector response. The Advanced Oxford Dictionary defines "simulation" as a situation in which a particular set of conditions is created artificially in order to study or experience something that could exist in reality or as the act of pretending that something is real when it is not. The simulations used in particle physics, belonging to the first class, make use of probability distributions by applying Monte Carlo (MC) techniques.

First Monte Carlo simulation programs were already developed in the late 1970s, and since then huge progress in complexity and methodology was made: Programs nowadays are able to make highly accurate predictions for most of the measurements performed at the LHC and elsewhere. They have thus become inevitable tools in all high energy physics experiments today, and consequently the continued and sustained development of Monte Carlo programs has been a major activity in the Terascale Alliance from the beginning. In line with the incredible technical developments in the computation of precision observables, the most important activity has been the quest for ever increased predictive precision in these tools.
Besides the implementation of new processes and of more advanced theoretical descriptions, a major step forward was obtained by adjusting free parameters of the models to measurements (a procedure dubbed "Monte Carlo tuning") as well as by estimating uncertainties of predictions. These two areas – together with contributions to the direct development of existing or new Monte Carlo generators – were focal points of Terascale Alliance activities. However, the networking and education aspects were also vital to the Alliance idea!

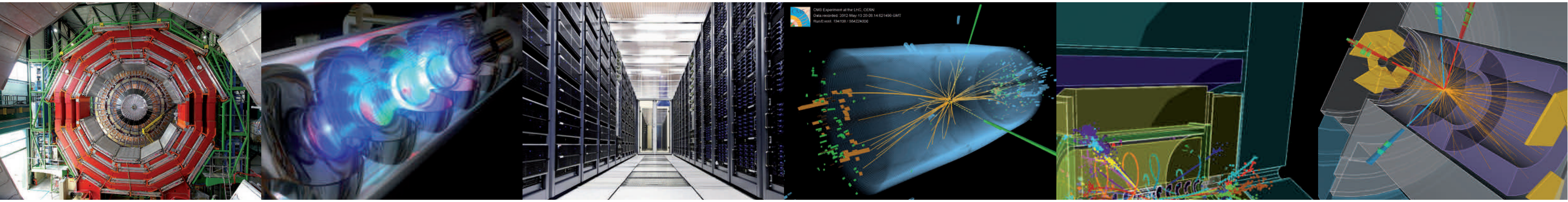


Figure 1: Poster of the 2015 Monte Carlo school

NETWORKS IN THE MONTE CARLO WORLD

Monte Carlo simulation programs are developed and maintained in collaborative efforts by distinct groups, and communication and exchange between these groups is essential. The German groups active in MC development and usage found a stimulating environment with the MC group meetings that were organised on a regular basis at DESY and with annual MC group meetings at other Alliance institutes. Annual MC schools educated a whole generation of students and postdocs in MC techniques and in the usage of MC programs: the schools continue until now and raise continuous interest both within Germany and abroad.

Discussions and scientific exchange are essential for a motivating, encouraging and exciting research: the "Theorist of the Month" programme allowed international experts to spend up to a week in the environment of the Analysis center and to have direct and fruitful discussions also with the experimental groups. A number of publications resulted from these visits. The "Resummation Institute" in the year 2009 triggered a series of annual expert workshops on "Parton Showers and Resummation" that took place at DESY (2012), in Durham (2013), in Muenster (2014) and in Cracow (2015). MCnet, a network for MC activities funded by the EU, was an international partner to the Terascale MC enterprise. Two German universities are nodes in this network, with DESY as a corresponding partner.

JOINING THE FORMULA 1 LEAGUE

The MC group worked out a very ambitious and challenging programme: from the development of new approaches to be used in Monte Carlo event generators (like a new formulation of parton showers and the usage of transverse momentum dependent parton density functions) over the tuning of existing MC event generators (to best describe existing measurements) to the development of service tools. A further goal was to play an active role in the experiment-specific MC activities within the ATLAS and CMS collaborations. Although this programme was very broad, it was often requested that the MC group should focus more on service tasks for the experiments. While in some special cases cross-experimental research could be performed, the experimental activities stayed essentially within the experiment. However, with its phenomenological programme, the Terascale MC activities jumped immediately into the international Formula 1 league of the Monte Carlo enterprise. Vital for the success of the MC activities were the new positions created within the Terascale Alliance: several tenured positions at different universities, including a young investigator group at KIT, and a tenure track and several postdoc positions at DESY. Without the additional person-power, the new activities would have not been possible. Below we highlight a few of the activities (without being able to do justice to the multitude of different activities

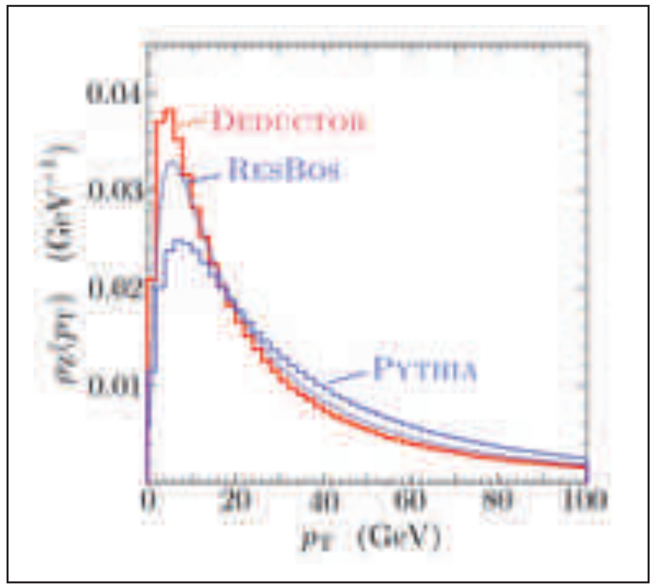


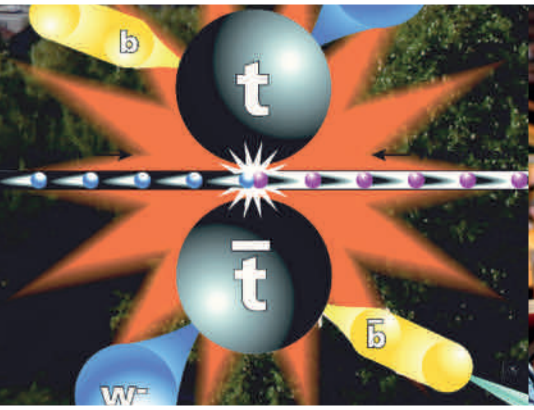
Figure 2: Transverse momentum spectrum of Z bosons in pp collisions at the LHC obtained from DEDUCTOR compared to various other predictions [6].

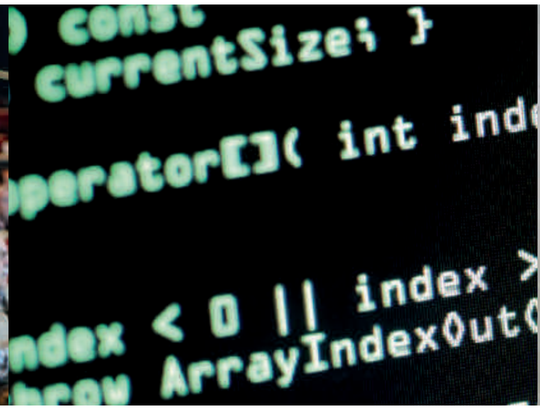
The development of Monte Carlo programs has been a major activity in the Terascale Alliance from the beginning.

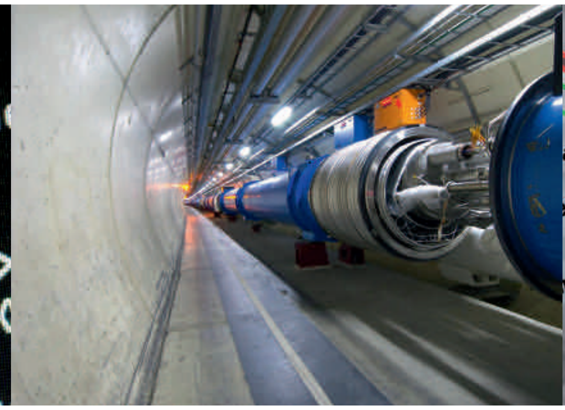
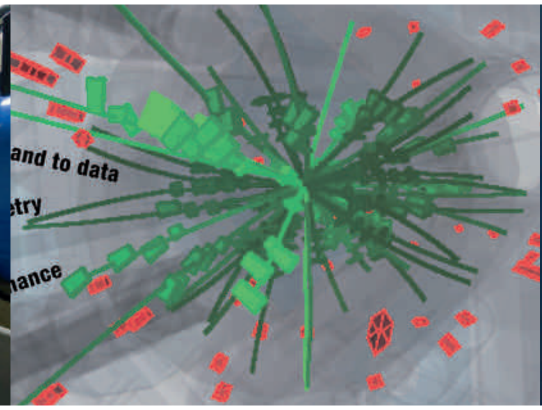
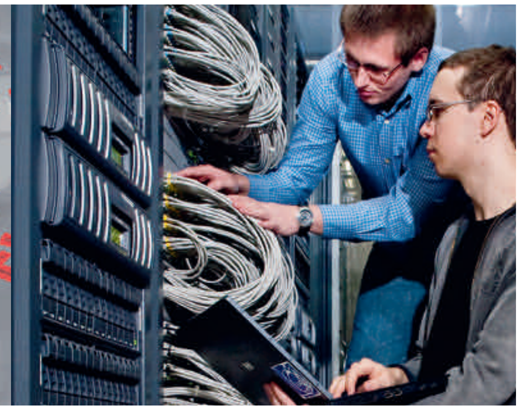
– see also the next two articles on the HERWIG and WHIZARD developments for more, and more detailed, information about specific Terascale MC activities):

THEORY DEVELOPMENT FOR PARTON SHOWER ALGORITHMS: Current parton shower algorithms are based on theory-motivated phenomenological models. One important goal of the MC group was – and is – to define parton shower systematically in the perturbative QCD framework by providing an all-order definition that can naturally be incorporated in fixed-order calculations. Furthermore, important work was done on the resummation of visible (such as jet p_T or Drell-Yan p_T) and invisible (threshold) large logarithms.

DEVELOPMENT OF MONTE CARLO PROGRAMS: The Monte Carlo group provided significant contributions to a number of modern MC generators (see also the following two articles in this brochure). Among them are CASCADE, DEDUCTOR, PYTHIA8, Herwig++, WHIZARD, HELAC, Sherpa, and VBFNLO. The CASCADE generator – the only generator to use transverse momentum dependent parton density functions – was extended by members of the MC group to LHC applications. DEDUCTOR has as its main guideline implementation of parton shower algorithms on a solid theoretical basis and to use only systematically improvable and well-controlled approximations. PYTHIA8 and HERWIG++ are the well-known C++ successors of the most commonly known and used MC generators in high energy physics, and significant contributions have been provided by members of the Terascale community. WHIZARD, finally, is a multi-purpose event generator heavily used for simulations of the physics at an e+e- machine. A special project here was the matching of threshold resummation calculations with continuum fixed-order NLO QCD corrections, allowing the very precise simulation of the top-quark threshold at an e+e- machine. For the LHC, the focus of WHIZARD is on vector-boson scattering; this option has already been used by ATLAS.





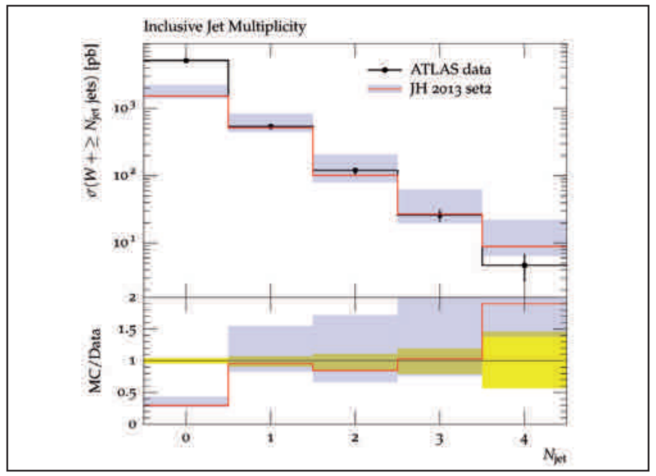


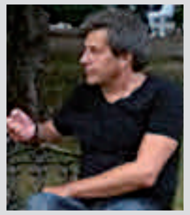
Figure 3: Predictions for jet multiplicity in W+jets production using CASCADE with the unintegrated TMD gluon density JH-2013-set2 (Nucl. Phys. B883 (2014) 1), compared to ATLAS data (Phys. Rev. D 85 (2012) 092002). The yellow (blue) band is the experimental (theory) uncertainty.

MC RESPONSIBILITIES IN LHC EXPERIMENTS: The experience gained within the Terascale MC group and the close connection between experimentalist and theorist helped to put Terascale physicists into leading positions within the experiments.
DESY scientist contributed as leaders of the ATLAS Monte Carlo group and the Monte Carlo Tuning sub-group and as MC software and production responsible. In addition, the DESY group performed Standard Model measurements with an emphasis on providing data for improving MC predictions. The broad knowledge on Monte Carlo tuning was recognised in a review article on Monte Carlo tunes of for the LHC.
The “Physics Comparison and Generator Tunes” group in CMS, lead by a scientist from DESY, profited much from the experience gained within the Terascale MC group. The responsible for the Rivet package in CMS also used his experience gained in the Terascale MC group.

TUNING MONTE CARLO EVENT GENERATORS: At the start of LHC Run 1 in 2009, the Monte Carlo predictions then available were obtained by extrapolating from lower energy experiments. With the first LHC data at hand, several tuning activities started. Specifically the tune performed by ATLAS members of the Terascale MC Group attracted a lot of attention. This tune was also then used in ATLAS central Monte Carlo production. The tunes were further improved when new sensible data appeared, leading to a series of tunes that is still continued today. Another milestone in the list of tunes was the first tune to NLO Monte Carlo generators. Also CMS tunes (CUET CMS Underlying Event Tunes) were obtained by scientists who had gained significant expertise on MC generators and data interpretation from the Terascale MC group.

TOOLS DEVELOPMENT: The development of (experiment-independent) tools was another focus of the MC group. Here, we want to mention a few selected examples for such developments.
With many different MC codes and their frequent updates, it is necessary to have an easy and flexible tool to perform Monte Carlo generator validation and comparison that allows the user to plot problems in new implementations and to find the optimal choice of generator and parameters for each analysis. **The HepMCAnalysis tool** was developed precisely for these purposes. It has been (and still is) in wide use for MC studies (during the Terascale MC schools, to mention one example) and in the MC generator validation by the Generator Services (GENSER) LCG project.
The increasing interest in parton densities that depend on the transverse momentum of the interacting parton made a library of existing parametrisations necessary. The **TMDlib** – together with the online plotting web portal TMDplotter – went online in 2014.
For the validation and tuning of MC generators, not only measurements from LHC but also from HERA are essential. The **Rivet** (Robust Independent Validation of Experiment and Theory) package, developed within MCnet, was extended with an interface to the well-known **HZTool** to allow easy and unified access of most of the HERA measurements.

Hannes Jung (DESY, left) and **Zoltan Nagy** (DESY, right) together with **Judith Katzy** (DESY), **Albert Knutsson** (then DESY, now U Antwerp) and **Serguei Levonian** (DESY) acted as convenors of the Terascale MC group.

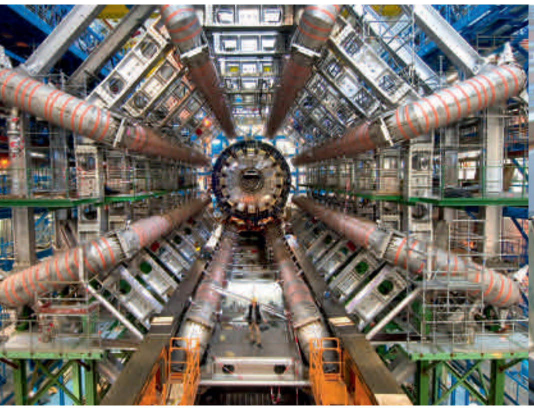



SUMMARY: The Terascale Monte Carlo group has successfully completed some of the open issues before LHC Run 1 started. New issues came up with the data recorded at the LHC, and new data from Run 2 will require continuing support and development of Monte Carlo generators as well as parameter tuning. Monte Carlo activities remain essential for a successful analysis and interpretation of collider measurements.

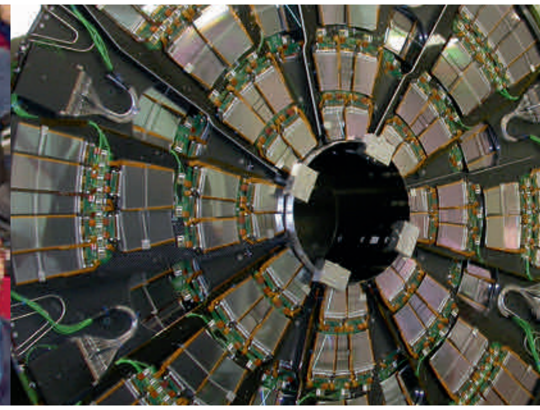
CONTRIBUTING TO THE DEVELOPMENT OF HERWIG++

A Terascale Monte Carlo project

One of the signature activities of the Helmholtz Alliance has been the ongoing development of Herwig++ [1], one of the three most important Monte Carlo simulation programs that are used throughout the LHC community. Herwig++ is a multi-purpose simulation package for collider physics at pp, ep and ee colliders and has been in regular use by the experimental collaborations since its first releases. The group of Stefan Gieseke at KIT together with Simon Plätzer at DESY Hamburg have been driving several developments within Herwig++ to match the ever-increasing precision of experimental data available from the LHC. This involves both more precise calculations and their combination with a fully realistic simulation, as well as improved phenomenological models.





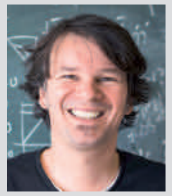
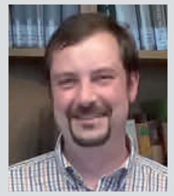



A important ingredient to collider event generators are algorithms for the simulation of subsequent radiation off a hard scattering. The structure of these algorithms is central to any attempt of combining higher order improved calculations with the full simulation. Within this setting, certain classes of such parton-shower algorithms turn out to be much more handy in the context of next-to-leading order (NLO) corrections in the strong interaction. Particularly algorithms based on a dipole splitting picture have recently gained a lot of interest. Within the Alliance activities we have not only pushed forward the theoretical understanding of such simulations, but also provided a fully-functional implementation with the Herwig++ event generator. This module provides an alternative to the standard shower module of Herwig++ and is vital to cross-validating uncertainties in the simulation arising due to unknown higher-order corrections. We have studied parton-shower radiation from various showers in collaboration with other parton-shower authors as well as experimentalists and the possibility to compare newly devised observables to experimental data. The results of these efforts will be published together with the OPAL collaboration.

Precision physics at the LHC is always linked to higher-order corrections for the underlying hard process of interest. These are subleading terms in the series expansion in the small coupling constant of the strong interactions. The resulting effects are present in every LHC event as the initial protons are strongly interacting particles and usually break up into colour-charged particles during practically all interactions of interest.
The higher-order corrections manifest themselves in so-called loop-corrections and in the additional radiation of particles. The aforementioned parton showers simulate the effect multiple corrections of this kind, while making simplifying assumptions. Now, when we want to improve our simulations with NLO corrections, we have to ensure that these corrections are not counted twice. In a long-term programme we have developed the module Matchbox of Herwig++ that can take NLO calculations and consistently add the parton-shower simulation on top of it, in a fully automated way. This new framework has succesfully been applied to state-of-the-art calculations for LHC Higgs+jets production and allows for the consistent combination of this new level of accuracy with both parton-shower modules available in Herwig++.
New concepts for the combination of multijet events at NLO have been developed and implemented and are subject to extensive studies.

As a multi-purpose tool, there are several ends where improvements of the simulation have to be made. In order to take into account details of the hadronic interaction that are beyond single hard interactions, we simulate a so-called underlying event with multiple partonic interactions. The theoretical framework of how these interactions are linked together is not well formulated and requires further research. We have also addressed studies of sub-leading colour effects that deal with these problems from a more theoretical point of view. Particularly the question of including subleading-colour effects has been pioneered within Herwig++ in a proof-of-concept implementation, and more theoretical development and new algorithmic concepts are underway. At the same time there are non-perturbative phenomena that have to be addressed as simple models. The earliest LHC data lead us to a study of these phenomena, which resulted in an improved simulation of multiple partonic interactions.
A new line of precision arises with the advent of yet higher-order corrections in the strong coupling. Electroweak corrections are deemed to become important in the context of LHC precision physics in the coming years. A first implementation of these corrections for vector boson pair production has been achieved alongside a proposal for an experimental setup that is sensitive to these corrections.

Stefan Gieseke (KIT, left) and **Simon Plätzer** (then DESY, now Durham and Manchester, right) are co-authors of the Herwig++ MC generator. Gieseke led a young investigator group financed by the Terascale Alliance, while Plätzer held a post-doc position in the Monte Carlo group of the Alliance. Both also contributed heavily to the Terascale MC schools.

[1] see the Herwig++ homepage https://herwig.hepforge.org.

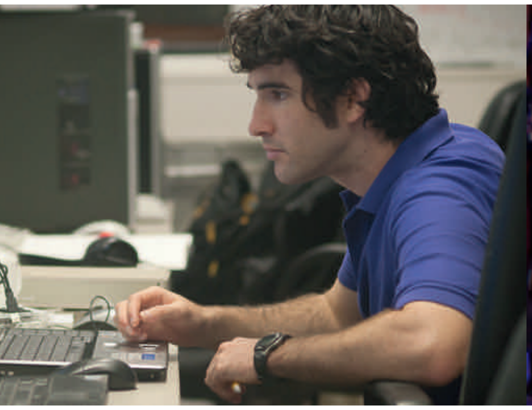
THE WHIZARD MONTE CARLO EVENT GENERATOR

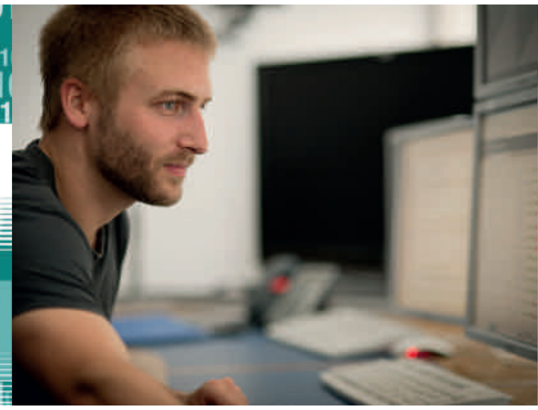
Magicians at the Terascale?

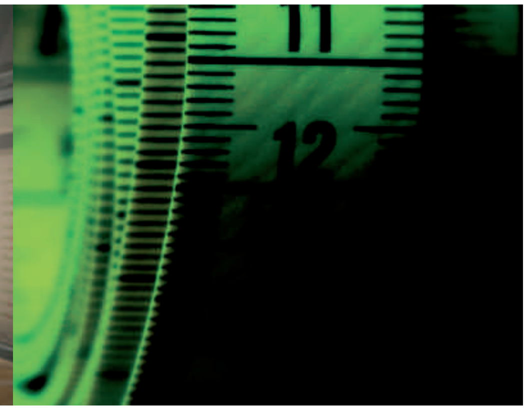
WHIZARD is a multi-purpose event generator that is mainly developed at DESY with smaller groups of one senior physicist plus 1-2 postdocs/students at the universities of Siegen and Würzburg. The project thus naturally fosters joint dissertation projects between different Alliance institutes. WHIZARD was and is the main workhorse for lepton collider physics: the mass productions of simulated collision events for the ILC conceptual and technical design reports as well as for the conceptual design report of the Compact Linear Collider (CLIC) have been done with WHIZARD!

Currently, also the CEPC project study (Circular Electron-Positron Collider, China) is using the WHIZARD expertise. The result is an intense collaboration with IHEP and Tsinghua University (Beijing, China), with numerous invitations of WHIZARD members to China in 2014 and 2015. In order to allow for large-statistics event production with different machine designs (ILC, CLIC, CEPC, ...), and in order to enable the experimental groups to study the effects of the machine design on the physics programs of a lepton collider, a lot of effort has been put into a realistic beam description for lepton colliders in WHIZARD, taking care of macroscopic beam effects (beamstrahlung) and initial-state QED radiation.

Figure 2: Participants of the WHIZARD workshop held in Würzburg in March 2015.







A major effort in WHIZARD is the automation of radiative corrections by interfacing external one-loop programs. In the DESY group, an automatic Frixione-Kunszt-Soper (FKS) subtraction scheme has been implemented, and the automatic generation of MC code for one-loop processes at lepton colliders for massless and massive QCD final states has been demonstrated. In addition, WHIZARD's own POWHEG implementation for the matching with the hardest emission from matrix elements and parton showers has been developed.

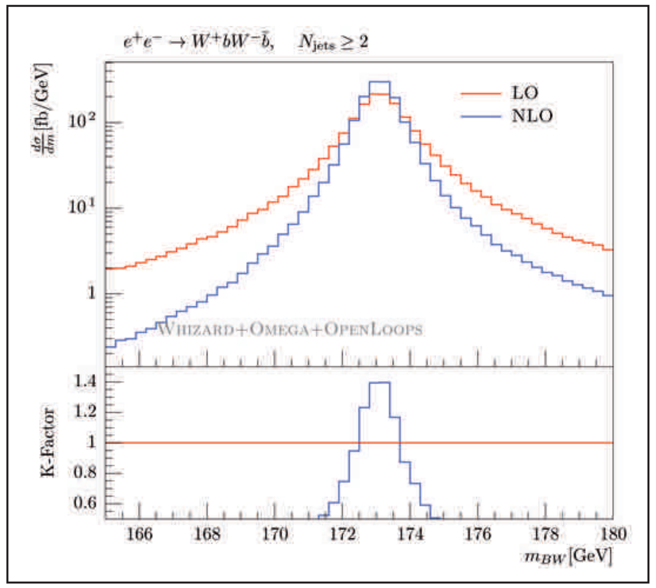
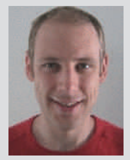


Figure 1: Distribution of the invariant mass of pairs of W bosons and b quarks in electron-positron collisions, $e^+e^- \to$ WbWb calculated with WHIZARD at leading order (red) and next-to-leading order (blue).

A special project is devoted to the matching of (more or less inclusive) NRQCD threshold resummation calculations with continuum fixed-order (relativistic) NLO QCD corrections in the WHIZARD framework. This matching will allow a more exclusive simulation of the top-quark threshold at an e^+e^- machine to be performed. This is of utmost importance because a study of this threshold is currently the only known possibility to measure the top-quark mass with a precision of 100 MeV or even better.

For the LHC, two main focus areas for WHIZARD are vector boson scattering (where WHIZARD has been used by ATLAS to determine the first-ever limits from LHC on deviations of quartic electroweak gauge couplings) and top physics, where WHIZARD is used by both ATLAS and CMS in the analysis of the $t\bar{t}\gamma$ final state.

Jürgen Reuter (DESY) is one of the WHIZARD authors. WHIZARD has received Alliance funds for the organisation of workshops and also travel support.

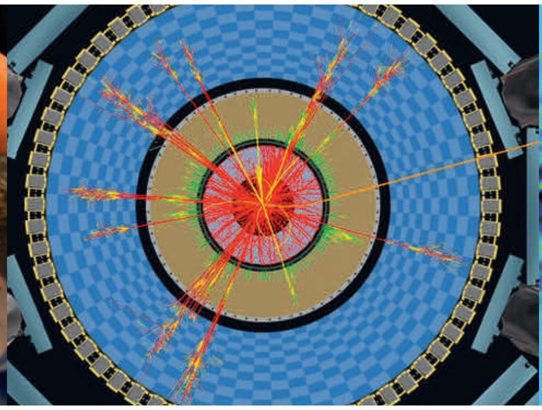
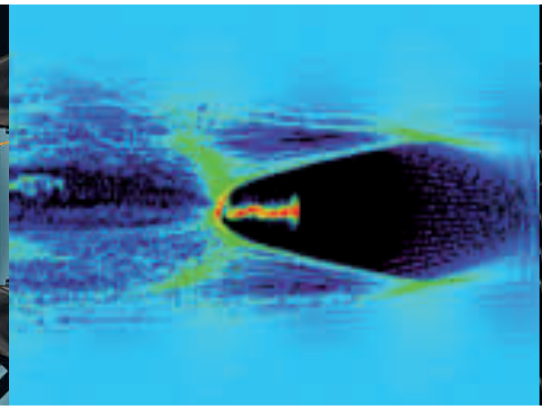
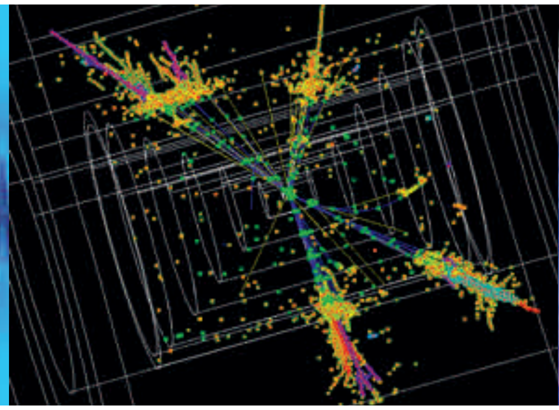
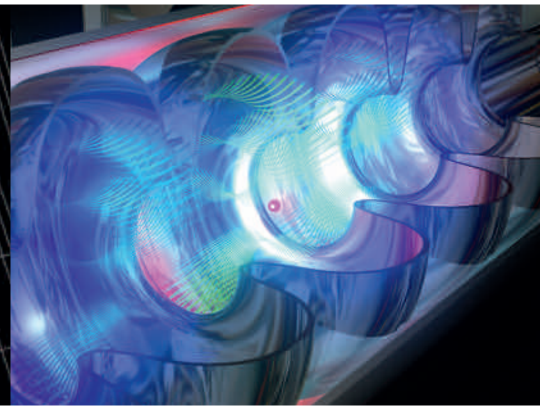


PARTON DISTRIBUTION FUNCTIONS

HERA heritage and prerequisite for discoveries at the LHC

The structure of the proton is a fascinating problem for both experimental and theoretical investigations. It is governed by a complex dynamics involving interactions of quarks and gluons, which – at high-energy colliders – can be described using a perturbative approach to quantum chromodynamics (QCD), the theory of strong interactions. In this approach, the proton may be viewed as a collection of weakly interacting partons, the momentum distributions of which are given by so-called parton distribution functions (PDFs).
Precise knowlegde of the PDFs is essential for the understanding of particle reactions at hadron colliders like the LHC. An example is the Higgs boson production rate measured by ATLAS and CMS, which is observed to be consistent with Standard Model expectations.

However, an accurate knowledge of the PDFs requires precise experimental data and complex theory calculations. Not least due to its past as home of the electron-proton collider HERA, DESY is the world-leading research center in the field. HERA was a unique experimental facility that provided a precise map of PDFs over a broad kinematic range. It is for this reason that it was decided, in the early days of the Alliance, to found a PDF activity that should strive to bundle the experimental and theoretical expertise available at DESY and in the German community and to support further investigations of the proton structure.


The PDFs are determined from QCD fits to experimental data, including results from lepton-proton and proton-proton collisions; they are given in terms of PDF sets. Today, several groups provide such sets, e.g. CTEQ, MMHT, NNPDF and JR.

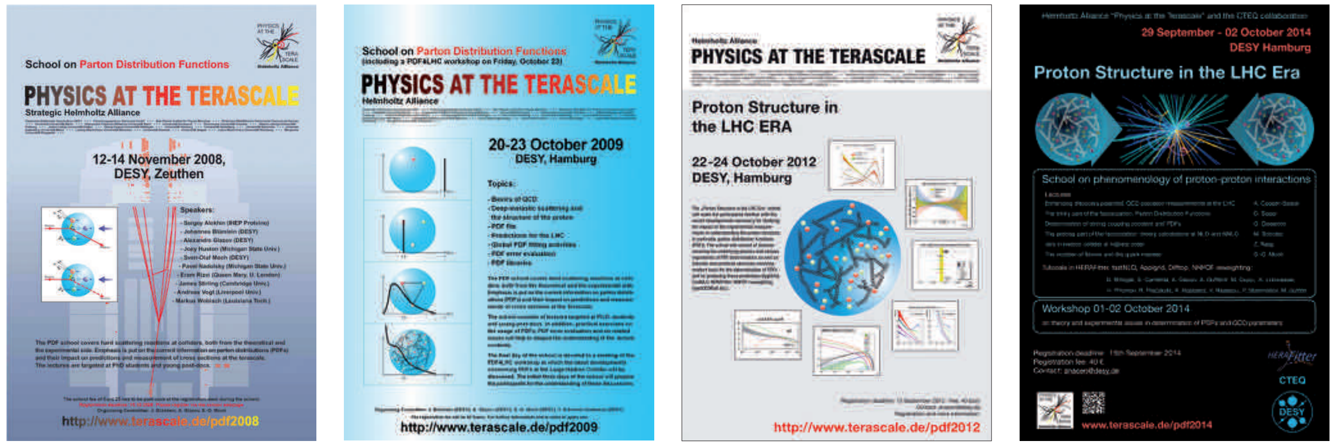


Figure 1: The posters of four Terascale PDF schools and workshops.

Figure 2: The participants of the first Terascale PDF school 2008.

Two sets, however, are derived with leading contributions from DESY and Alliance scientists: the ABM and HERAPDF sets. Both the ABM and the HERAPDF group have a long history, and their support and collaboration has since long been a goal of the Alliance PDF activities. While the ABM set focuses on the treatment of the data using the best-known theoretical predictions, the HERAPDF set uses the HERA data alone, providing a reference for the data usage.

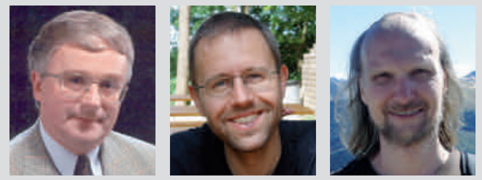
Today, the experimental investigations of the proton structure continue within the ATLAS and CMS experiments at the LHC where DESY groups play important role in the Standard Model studies that provide additional constraints on PDFs. The DESY theory group provides essential predictions for physics processes at the LHC and the important interpretation of the data. Today, thanks to the immense experimental and theoretical effort, the PDF uncertainty for important physics – e.g. the search for new physics – is at the percent level.

The proliferation of the PDF sets made it important to benchmark them with respect to each other. Many sets use proprietary codes making detailed comparisons difficult. The ABM group has decided to use an open-source model for its code development using the OPENQCDrad programme. The HERAPDF effort became the core of the HERAFitter activity, an open-source QCD analysis program. The aim of the HERAFitter is to provide a community-supported platform for QCD analysis using up-to-date tools for the data treatment and theoretical calculations.

OUTREACH: SCHOOLS AND WORKSHOPS

The PDFs are in particularly important for the measurements at the LHC. A number of dedicated PDF schools and workshops have been supported by the Helmholtz Alliance with a primary goal of connecting PDF users from the LHC experiments (mostly Ph.D. students) with the leading experts. Two schools were organised before the start of the LHC operation and two after. The last two schools were focused on giving hands-on experience for the HERAFitter code and for other tools that are commonly used in QCD analyses. All schools can be found in INDICO[1].

Johannes Blümlein (DESY, left), **Sven-Olaf Moch** (then DESY, now U Hamburg, centre) and **Alexandre Glazov** (DESY, right) were the first convenors of the Terascale Alliance PDF activities.



[1] https://indico.desy.de/categoryDisplay.py?categId=127.

DEVELOPMENTS OF THE ABM PDF SET

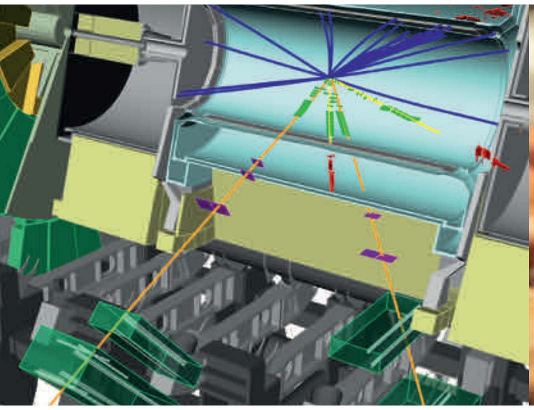
Theory-driven PDF developments

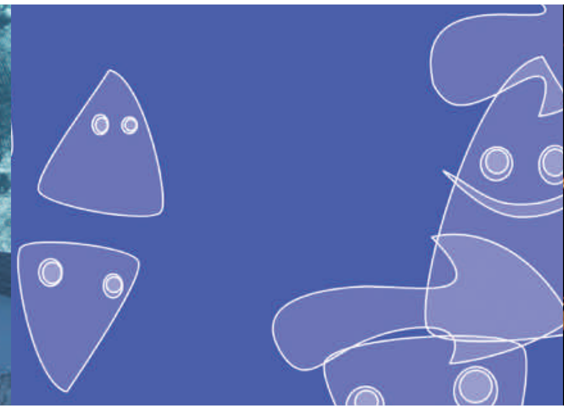
The ABM collaboration aims at precision PDF distributions at 2- and 3-loop order, including a proper decription of heavy-flavour effects and a detailed description of the flavour decomposition of the quark sea. The ABM analysis is based on the world precision data on deep-inelastic scattering and on reliable hadron collider data that are sensitive to the different PDFs. Moreover the collaboration considers the correlations between the fit parameters and provides the corresponding correlation matrices, accounting both for the statistical and systematic errors of the data. In particular, the correlation of the strong coupling constant to the other fit parameters is of importance. In case of deep-inelastic scattering, higher twist effects in the range of lower virtualities Q^2 have to be considered. During the last years, the collaboration released three PDF sets[1], dedicated comparative predictions on the production cross sections for W and Z bosons, top quarks and the Higgs boson at the LHC for different collision energies, and the correlated determination of the charm-quark mass in deep-inelastic scattering data. Very recently, the collaboration has performed detailed simulations of the Drell-Yan process for weak boson production at ATLAS, CMS and LHCb and for the lepton asymmetries measured at the Tevatron and the LHC.

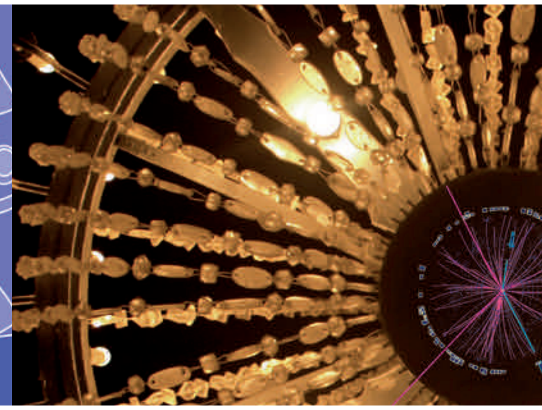
In Fig. 1 we present a summary of the ABM PDFs and compare them to other PDF sets. Not all PDF sets agree – a fact that will be addressed by upcoming LHC precision measurements. Figure 2 illustrates the precision determination of the charm-quark mass based on HERA data. The result is competitive with other precision analyses.

Serguei Alekhin (IHEP/DESY), **Johannes Blümlein** (DESY, left) and **Sven-Olaf Moch** (then DESY, now U Hamburg, right) are the authors of the ABM PDF sets.

[1] S. Alekhin, J. Blümlein and S. Moch, Phys. Rev. D89 (2014) 5, 054028 [arXiv:1310.3059 [hep-ph]].







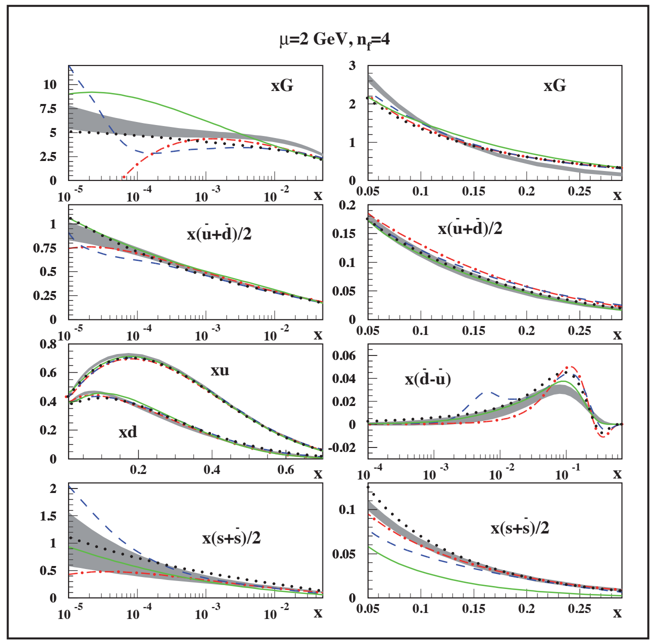


Figure 1: The 1σ band for the 4-flavour NNLO ABM12 PDFs at the scale of μ = 2 GeV versus x (shaded area) compared with the ones obtained by other groups (solid lines: JR09; dashed dots: MSTW08; dashes: NN23; dots: CT10)).

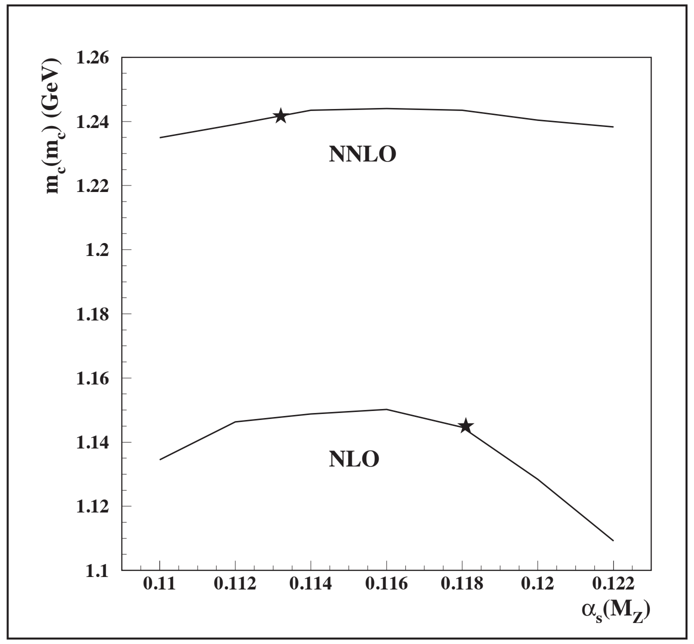


Figure 2: The values of the charm-quark mass $m_c(m_c)$ obtained in the NLO and NNLO variants of the ABM11 fit with the combined HERA charm data included and the value of α_s (M_Z) fixed. The position of the star displays the result with the value of $\alpha_s(M_Z)$ fitted.

DEVELOPMENT OF THE HERAFITTER TOOL

A platform for PDF developments

The first release of the HERAFitter-0.1.0 open-source QCD analysis platform was performed in September 2011. At that time the code was released as a joint project of the H1 and ZEUS collaborations and included computations required to reproduce the HERAPDF1.0 set from the combined HERA data. The program already included code specifically developed for the prediction of Drell-Yan production at the LHC as well as interfaces to fast computation programs. The following “beta releases” (versions 0.2.0, 0.3.0), scheduled approximately on a yearly basis, further extended the functionality of the code by including more data and theory predictions. The first stable release – HERAFitter-1.0.0 – in December 2013 represented a mature code that included predictions based on models from the main PDF groups and data from fixed-target experiments, HERA, Tevatron and LHC. The stable release was followed by the HERAFitter general description paper and by a further release of HERAFitter-1.1.0 in September 2015 (which among other additions provided a migration to the LHAPDF6 format). In addition to supported releases, the trunk of the package is open for read access and contains the latest developments. The next stable release, version 1.2.0, is scheduled for summer 2015.

HERAFitter has by now become a major project that is independent of the HERA collaborations. The activities are lead by the HERAFitter conveners, and a steering board with representatives from the theory community and from various experiments oversees the developments. There are weekly developers meetings, which have restricted access, and regular users meetings, which have open access. All activities of the HERAFitter developer’s team are documented on a dedicated web page (see below).

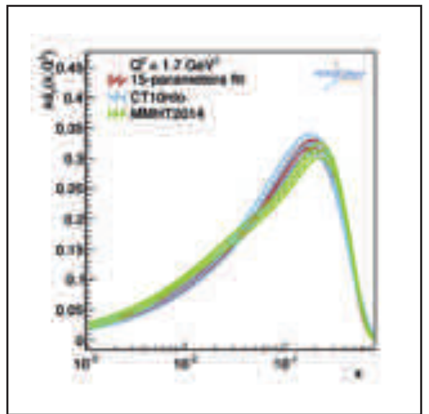


Figure 1: d-valence PDF at the scale Q^2 = 1.7 GeV^2 as a function of Bjorken-x determined from a fit to the HERA I and Tevatron W- and Z-boson data using the HERAFitter framework, and from the CT10nlo and MMHT2014 PDFs.

The current version of the HERAFitter program contains all components required for a modern QCD analysis. The QCD evolution can be performed up to next-to-next-to leading order using the QCDNUM and, recently implemented, APFEL codes. The deep-inelastic scattering cross section can be computed using fixed-flavour and variable-flavour schemes following the prescriptions from all major PDF groups. The predictions for proton-(anti)proton scattering processes can be computed using APPLGRID and FastNLO. The theory predictions are combined with the data using a flexible interface. The data representation permits complex correlation models with systematic uncertainties shared by several data sets. The code is optimised for fast execution, and several branches of the code include OpenMP for parallel computation. The HERAFitter program contains complex diagnostics and plotting tools, and there are further tools for operations with LHAPDF6 sets, such as PDF reweighting and profiling.

The HERAFitter program has been used for a number of experimental and theoretical analyses. This is reflected in more than 20 papers published since 2012 and a few unpublished studies. The results using HERAFitter were presented at a number of conferences (more than 40 since 2013), including dedicated talks at high-high profile conferences such as Moriond QCD. Apart from publications by the external users, the HERAFitter developers released three papers signed by the HERAFitter developers team.

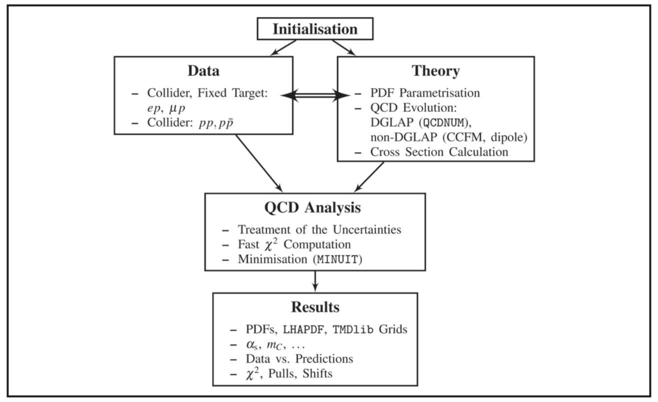
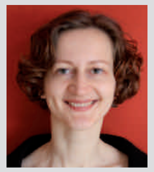


Figure 2: Schematic overview of the HERAFitter program

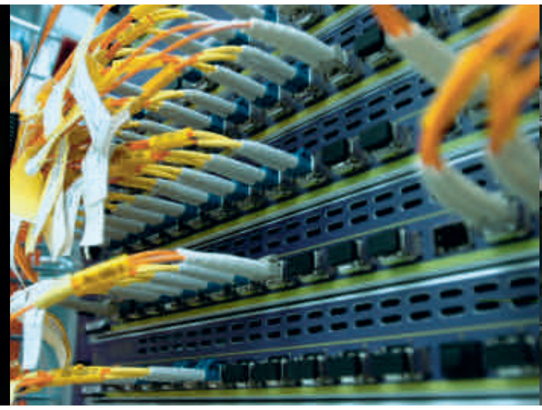
Figure 3: The HERAFitter core developers team.

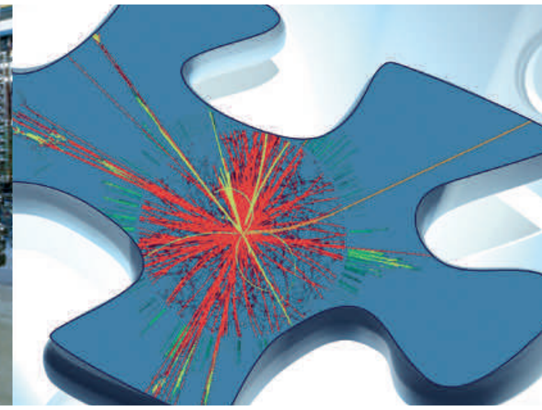
The development of the HERAFitter project received a significant support from the Helmholtz Alliance. The DESY IT department arranged a dedicated server for the HERAFitter developments and provided resources on the DESY computing farm. The HERAFitter web page and svn repository for the HERAFitter code are hosted by DESY. The Alliance supported two post-doc positions for the HERAFitter project. A number of visits for HERAFitter researches to DESY were supported, which were shared with other grants such as BMBF and HL.

From left ro right: **Ringaile Placakyte** (DESY) and **Voica Radescu** (U Heidelberg) are the current HERAFitter convenors. **Alexandre Glazov** (DESY) is release coordinator, and **Hayk Pirumov** (DESY) is software librarian.










ANALYSIS WORKING GROUPS

Concentrating Alliance forces on important topics

THE CENTRAL JET VETO WORKING GROUP

The Central Jet Veto Working Group was a joint enterprise of experimentalists and theorists. It had the overarching goal of improving analysis strategies for vector boson fusion processes, the Higgs production modes with the cleanest signature at the LHC. Vector boson fusion processes are characterised by two hard jets in the forward and backward regions of the detector. Decay products of the Higgs bosons are typically located in between these jets. Central jet veto techniques make use of the limited jet activity in the central rapidity region of the detector that helps to distinguish the vector boson fusion signal from omni-present background processes with ample jet activity.

The working group started out with introductions by theorists to the tools they had developed for the use by experimentalists. The format of very informal mini-workshops provided the ideal atmosphere for questions from the users to the developers and for discussions among them, and it gave theorists a platform to present their most state-of-the-art programs.

An important part of the activities before the discovery of the Higgs boson focused on vector-boson production processes in association with jets, and in particular on W+2-jet and Z+2-jet production at the LHC. Because of their similar characteristics, and because of the fact that these processes have large production cross sections, they provide an interesting test bed for the production of Higgs bosons together with two jets.

With the accumulated luminosity increasing, vector boson scattering processes have become accessible to the LHC experiments. In particular, ATLAS and CMS have published the observation of same-sign vector boson pair production in association with two jets. This class of reactions is very sensitive to the electroweak sector of the Standard Model and opens a window to new physics in the gauge boson sector. The Central Jet Veto Working Group discussed the related opportunities in great detail and developed dedicated analysis strategies for vector boson scattering processes. In addition, theorists provided Monte Carlo tools for the simulation of these processes and discussed the limitations of simple models for new physics in the weak sector. An in-depth assessment of vector boson scattering processes has also been performed in the context of the international workshop[1] on anomalous quartic couplings at the Technical University of Dresden that was sponsored by the Terascale Alliance.
All in all, the work of the group proved to be very useful especially in the early times of LHC data taking. The very informal collaboration between experimentalists from ATLAS and CMS and theorists clearly was key to the impact on the chosen analysis strategies.






HIGGS FINAL STATES AT THE LHC

In preparation of the Higgs searches and analyses at the LHC, it was important to understand the theoretical predictions for the most important production processes. Since the Higgs boson couples to mass, these processes always involve heavy particles. For example, the Higgs boson can be radiated off a top quark, which may either be completely virtual (gluon fusion), or occur in the final state of the process (associated ttH production). Both processes are theoretically very challenging, from the technical as well as the conceptual point of view.
In an effort to bring together experts from theory and experiment in this field, we initiated a Working Group within the Helmholtz Alliance with the goal of pinning down the proper theoretical description for these processes, in particular in the light of the experimental requirements. The kick-off workshop for this working group took place at Bergische Universität Wuppertal in March 2010[2].

At about the same time, the LHC Higgs Cross Section Working Group was being established[3]. In order to avoid duplication of structures and to focus efforts, it was decided to integrate the Alliance working group into this much larger enterprise. In fact, many of the participants of the kick-off workshop took over leading roles in the LHCHXSWG, for example as conveners of dedicated subgroups for particular Higgs production processes.

The experience with the group shows a specific feature – or problem – in the design of Terascale activities: In case of great success of initiatives or of great need for action, activities tended to be drawn towards CERN, where the centre and the heart of all LHC-related work lies. This does, however, not exclude significant contributions from Terascale physicists to these endeavours.

[1]http://www.terascale.de/aqgc2013
[2]https://indico.desy.de/conferenceProgram.py?confId=2705
[3]https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

Ulla Blumenschein (U Göttingen, left) and **Barbara Jäger** (then U Würzburg, now U Tübingen, centre) were convenors of the CJV working group. **Robert Harlander** (U Wuppertal, right) was one of the convenors of the Higgs final states working group.

THE $\tau\tau$ ANALYSIS WORKING GROUP

Studies of processes involving τ leptons are a somewhat special but important and interesting part of the ATLAS and CMS physics programme.
The Higgs boson decay into pairs of τ leptons was so far the last channel for which evidence could be established based on the data from the first phase of the LHC operation (see Fig. 1); at the same time it provided the first direct evidence for the Higgs boson's interaction with fermions: The initial discovery in 2012 was based purely on Higgs decays to bosons. The τ channel will also continue to offer options to measure Higgs boson properties that are complementary to other decay modes.
In addition, τ leptons are a potentially powerful probe for new particles, for example additional Higgs bosons or heavy versions of W and Z bosons, that are predicted by theories extending the Standard Model of particle physics.

Experimental challenges arise from the facts that τ leptons are not stable and that most of their decays result in jets of light hadrons. They are thus difficult to distinguish from ordinary jets that are ubiquitous products of the proton-proton collisions at the LHC. Also, all τ decays result in undetectable neutrinos, which makes it difficult to precisely infer the original τ direction and energy from its decay products. The escaping neutrino also affects the calculation of the Higgs Boson mass in $H \rightarrow \tau\tau$ candidate events, a key quantity in extracting the Higgs signal from the data.

Both in ATLAS and CMS, German groups have been playing a strong role in the area of τ physics. While the final data analyses are defined and performed within the individual collaborations, the $\tau\tau$ working group of the Terascale Alliance has provided a unique forum for the informal discussion of some of the underlying concepts between experts from both experiments and also for the exchange of ideas with interested theorists. This concerns, for example, algorithms for the identification of τ-lepton decays, the reconstruction of the invariant mass of the $\tau\tau$ pair, or ideas for future measurements of additional Higgs-boson properties. Methods to model background processes producing signatures very similar to $H \rightarrow \tau\tau$ signal events based on collision data instead of simulation are another area of fruitful cross-experiment discussion, in particular a so-called τ-embedding technique, where the muons from $Z \rightarrow \mu\mu$ collision data events are replaced with τ leptons from simulated $Z \rightarrow \tau\tau$ decays.

Since the initiation of the $\tau\tau$ working group in 2008, thirteen two-day workshops have been held at ten different institutes. In addition to the typically 20-30 participants from German groups, numerous external guest speakers were invited, thus enriching the programme as well as carrying the discussions and results back into the international collaborations and theory communities.

From left to right: **Michael Kobel** (TU Dresden), **Jürgen Kroseberg** (U Bonn), **Günter Quast** (KIT) and **Alexei Raspereza** (DESY) were convenors of the $\tau\tau$ working group.

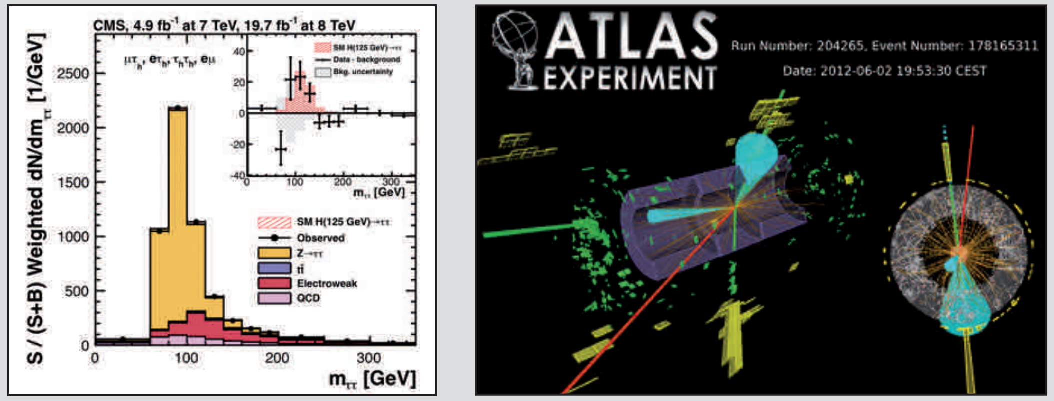


Figure 1: Left: $H \rightarrow \tau\tau$ signal observed by the CMS experiment, illustrated by the observed and expected distributions of the invariant $\tau\tau$ mass. The inset shows the corresponding difference between the observed data and expected background distributions, together with the expected $H \rightarrow \tau\tau$ signal (JHEP05 (2014) 104). Right: Display of a $H \rightarrow \tau\tau$ candidate event recorded with the ATLAS detector, where one τ lepton decays into hadrons, including one charged pion (indicated by a green track), and the other into a muon (indicated by a red track); the $\tau\tau$ invariant mass is measured to be 129 GeV. In addition, two high-energy jets are found in the event, marked by turquoise cones (source: ATLAS).

SELECTED DETECTOR R&D PROJECTS

Exploiting the VLDT infrastructures

The Alliance has so far supported twelve detector R&D projects (see table 1 on page 22). The following few examples may serve to illustrate the spirit and impact of these projects.

RADIATION-HARD SILICON SENSORS FOR THE SLHC
Participating institutes: Hamburg, Karlsruhe
The groups at Hamburg and Karlsruhe have strong expertise in the characterisation, analysis and design of radiation-tolerant silicon sensors. Within this project, they joined their resources and worked together on an improved understanding of the mechanisms of radiation damage in silicon, and on ways to improve the radiation hardness of silicon sensors for Terascale experiments.

The measurements concentrated on the effects of radiation on sensor strip parameters as well as on the charge collection of mini-strip sensors of various materials and technologies. Radiation-induced defects have been characterised using different spectroscopic techniques, charge collection, and pulse shapes for both pad and strip sensors. The available equipment (TCT, m-TCT) and the expertise in both institutes allowed for measurements of the charge collection efficiency (CCE) and the extraction of electric field profiles and trapping times. These measurements were complemented both at Hamburg and Karlsruhe by simulations of the performance of silicon sensors after irradiation. Using different measurement techniques, like DLTS (deep-level transient spectroscopy) and TSC (thermally stimulated currents), it was possible to identify the defect levels responsible for the current behaviour and for the effective doping profile in sensors in which the active volume was decreased by deep diffusion.
Using the m-TCT setup (multi-channel transient current technique) built-up and operated at Hamburg (see page 25), charge multiplication in irradiated pad sensors and the charge collection in sensors with integrated fan-outs have been studied. In addition, a new setup allowing precision measurements of the charge collected in pad diodes using electrons from a radioactive source has been made available. The results of this project have contributed to a much improved understanding of radiation damage in silicon sensors and have helped to define sensor designs suitable for operation at the high luminosity phase of the LHC.

VIRTUAL SIPM LABORATORY (VSL)
Participating institutes: Aachen, DESY, Hamburg, Heidelberg, MPI Munich, Wuppertal
Silicon photomultipliers (SiPMs) are novel light-sensitive detectors with a huge potential in many high energy physics detectors. They just emerged around the time when the Alliance started. The Alliance has initiated a Virtual SiPM Laboratory (VSL) in an attempt to bring together all German groups working on SiPMs and to strengthen their research efforts. The activities of the VSL members comprised

- the CALICE Analog HCAL project (DESY/HH, Munich, Heidelberg, Wuppertal),
- SiPM characterisation and testing (DESY/HH, Heidelberg, Munich),
- development of SiPM readout electronics (Heidelberg),
- SiPM response modelling and simulation of combined scintillator/SiPM systems (Aachen, DESY/HH, Munich, Heidelberg),
- optical calibration of SiPMs (DESY/HH, Wuppertal),
- and medical applications of SiPMs (DESY/HH, Heidelberg).

The Alliance has supported the ASIC development by funding the submission of several test chips, the design and construction of a portable SiPM training platform for students and newcomers in this research field, the adaptation and further development of available infrastructure, work on the CALICE AHCAL calibration system, and the simulation of scintillator/SiPM systems.

The development of SiPM readout chips (KLAUS and STiC) was heavily based on the VLDT infrastructure at Heidelberg. The KLAUS chip, dedicated to highly granular calorimetry with low power consumption, high signal-to-noise ratio (SNR) and large dynamic range, has been thoroughly tested and shown to have a factor of three higher SNR than the SPIROC chip presently used by the CALICE collaboration. The second chip (STiC) is aimed at fast readout of SiPMs used in time-of-flight measurements in high energy physics and in medical applications.

The SiPM portable test-stand was developed to allow easy and flexible measurements of SiPM parameters like dark rate, cross-talk, gain, IV curve, signal decay time, etc. Test-stands have been delivered to the universities of Bonn and Hamburg and can, on request, be made available to further groups.

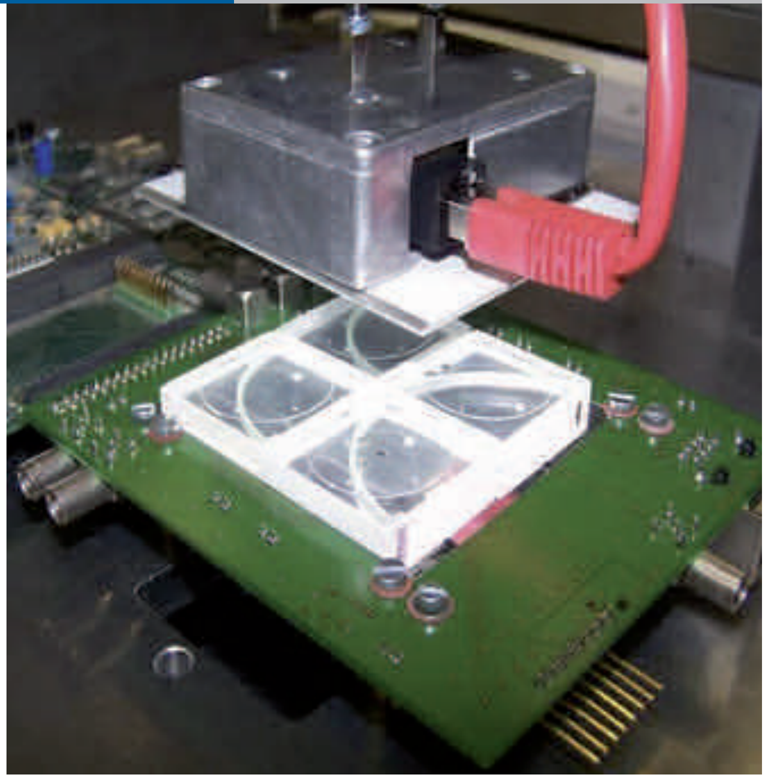


Figure 1: Scanning setup for scintillator tiles in Wuppertal.

A test stand built in Wuppertal allows the user to scan scintillator tiles optically and thereby to investigate their light yield, homogeneity, and the SiPM response (Fig. 1). The whole test stand is temperature-controlled; hence the temperature dependence of the response can be studied as well. A second test setup has been installed in order to study the yield and time structure of LED light signals with a photomultiplier and the long-time stability of the UV-LEDs.
In the framework of the VSL and the AIDA project, the MPI Munich has established a high-resolution SiPM scanning setup, which has successfully demonstrated the capability to measure the active area („fill factor“) on a pixel-by-pixel basis over the full sensor surface. In addition, based on the LED system developed at Wuppertal, MPI is constructing a test

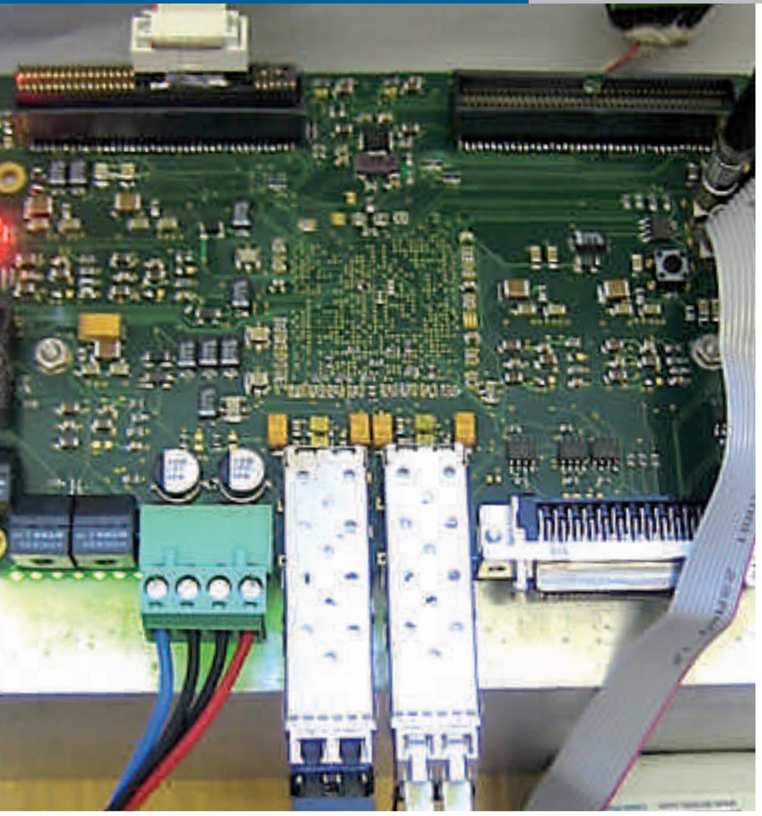


Figure 2: The front-end transceiver test board with two pluggable optical transceiver modules.

stand to measure the influence of the photon propagation in scintillators on the timing properties of plastic scintillator SiPM systems.

Aachen has studied a concept that involves scintillator tiles with wavelength-shifting fibers and SiPM readout. The light transport inside so called "light mixers", which are employed to homogenise the light coming from the wavelength-shifting fibers to the active area of the SiPM in order to guarantee the optimal usage of the dynamic range, has been simulated. The tile design has been optimised, and a setup to test the tile's efficiency and response to muons has been prepared. Heidelberg is also working on simulations of combined scintillator/SiPM systems using Geant4 and a newly developed custom-made SiPM simulation. An essential part of the studies is the simulation of the SiPM response, which has been developed during the last year in Heidelberg. First simulation results show excellent agreement with SiPM characterisation measurements in the full dynamic range of the sensors. Several institutes (e.g. DESY/Hamburg, MPI Munich) expressed their interest in using this simulation for their studies.

A TEST BENCH FOR A FAST DATA TRANSMISSION LINE

Participating institutes: DESY, Heidelberg, Wuppertal

In this project, the groups from Heidelberg (including ZITI Mannheim), Wuppertal and DESY, all interested in high speed optical communication, joined forces to develop a test bench allowing in-depth analysis of fast data links.

A suite of boards, firmware, and software have been devised and commissioned. The main work was done either on commercial evaluation boards for firmware development and test or using a transceiver board developed in Heidelberg with a dedicated firmware (see Fig. 2). In this way, several FPGA platforms have been studied, from the XILINX 5 to 7 families and also from the Altera GX FPGA series. Depending on the bandwidth needed, all chips and platforms are validated to serve as test bench engines. The produced firmware can be ported to newer chip versions.

The adaptation of the optics under test was done using several approaches. On the Heidelberg FPGA board, there are plugs for SFP form factor optics, and for all other devices adaptor boards have been developed to be connected to the FPGA board using a standardised high-pin-count connector (FMC). In this way, different commercial optics have been connected. Array-based and single-channel devices have been used.

Tests in terms of sending and receiving data correctly have been performed under lab conditions and in radiation areas. Both were very successful. The Heidelberg board could be operated under irradiation conditions: the FPGA withstands 200kRad. In all tests, bit error rates of 10^{-14} could be reached without problems. Together with a fast oscilloscope, eye-diagram measurements underline the signal quality of the devices under test. The test bench, nevertheless, must be adapted to the detailed specifications of the setup it is foreseen for, i.e. speed, signal types, encoding schemes, radiation etc. The collaboration has proven the possibility to do this and generated many useful tools for this purpose.

AGEING AND BACKGROUND SENSITIVITY OF PARTICLE DETECTORS

Participating institutes: Munich

The tandem accelerator of the Maier-Leibnitz Laboratory at Garching has been made available through the Alliance for ageing and background sensitivity studies with 20 MeV protons and high-energy neutrons (MeV range). The goal was to test gaseous particle detectors under high-background conditions.
The 20 MeV proton beam can be used for localised irradiation with beam spot sizes from 1 mm² to 1 cm². By wobbling the proton beam spot, sizes of 7 cm times 1 cm are possible. This experimental setup was applied for ageing studies of drift tube detectors.
A neutron irradiation facility was established to test gaseous detectors with highly energetic neutrons on large areas in high-background environments. For that purpose, three different neutron creation reactions were investigated: the breakup of 20 MeV deuterons on beryllium solid state targets, 30 MeV α particles on beryllium solid state targets, and 60 MeV boron ions on gaseous hydrogen. The characteristics of the created neutrons were determined by a newly developed neutron beam monitoring system. This monitoring system consists of pulse shape discrimination (PSD) detectors, which distinguish between neutrons and particles. The neutron flux measurements were performed with γ-insensitive BF3 counters.

With the above-mentioned neutron creation reactions, high-energy neutrons with energies from 7 MeV to 11 MeV and high background rates from $1 \cdot 10^4$ Hz/cm² to $1 \cdot 10^7$ Hz/cm² can be produced.

The detector R&D projects illustrate the spirit and impact of the VLDT infrastructures.

A large set of measurements has been carried out at this newly established facility by local and outside groups, including ageing studies of ATLAS MDT drift tubes, high-rate proton irradiation of diamond detectors, proton irradiation of a scintillating fiber detector, muon efficiency and tracking resolution of 15 mm drift

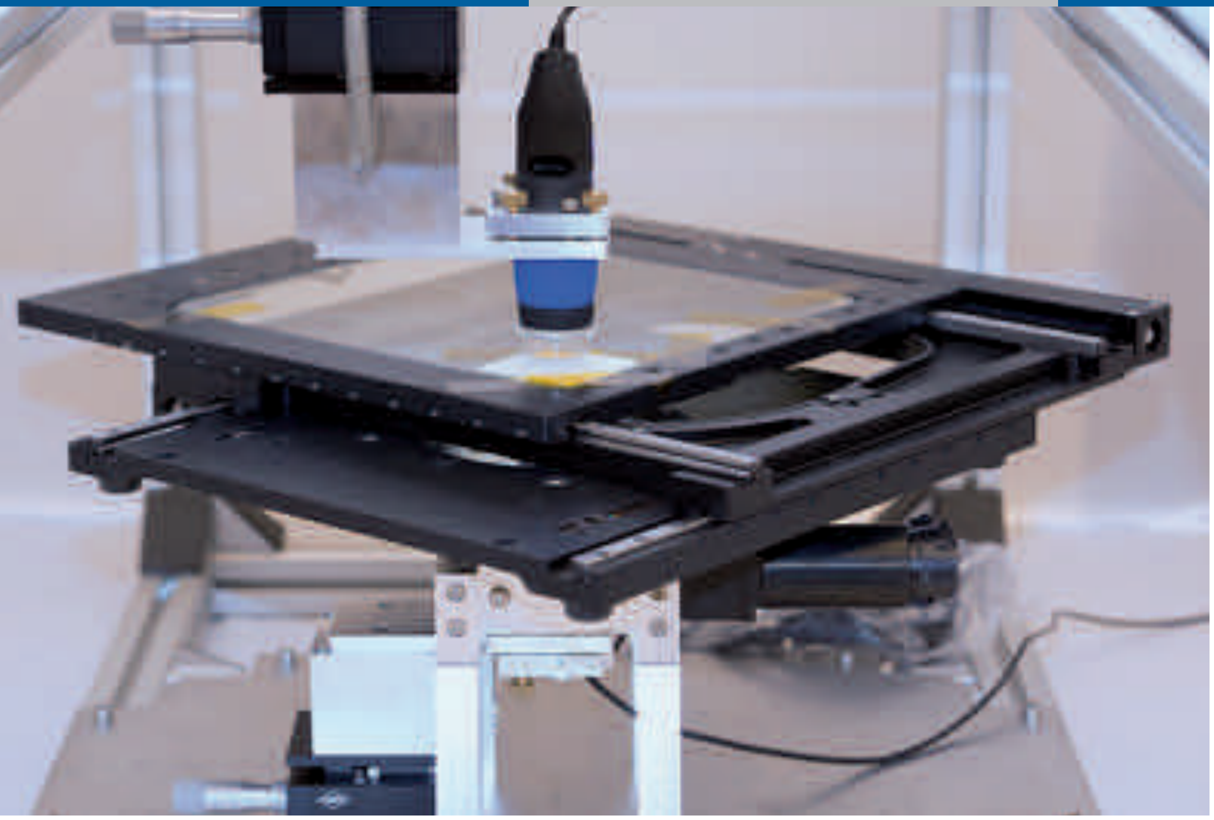


Figure 3: Prototype of a double sided metrology machine.

tubes in a 20 MeV proton background field, comparison of the sensitivity of 15 mm drift tubes and micromegas detectors to high-energy neutrons, and a study of the analogue signal shape induced by 20 MeV protons in 15 mm drift tubes.

ENABLING TECHNOLOGIES FOR SILICON MICROSTRIP TRACKING DETECTORS AT THE HL-LHC

Participating institutes: Aachen, Berlin, DESY, Freiburg, Hamburg, Karlsruhe

The tracking detectors of the ATLAS and CMS experiments have shown excellent performance in Run 1 of LHC data taking and are expected to continue to do so during LHC operation at design luminosity. Both experiments will, however, have to exchange their tracking systems when the LHC is upgraded to the high-luminosity LHC around the year 2024. The new tracking systems need to operate in an environment in which both the hit densities and the radiation damage will be about an order of magnitude higher than today. In addition, the new trackers need to contribute to the first-level trigger in order to maintain a high data-taking efficiency for the interesting physics processes. Novel detector technologies have to be developed to meet these very challenging goals.

The German groups active in the upgrades of the ATLAS and CMS tracking systems have formed a collaborative „Project on Enabling Technologies for Silicon Microstrip Tracking Detectors at the HL-LHC“ (PETTL), which was supported by the Alliance during the years 2013 and 2014. The aim of the project was to share experience and to work together on key areas of mutual interest during the R&D phase of these upgrades.

Five work packages have been selected: (1) exchange of experience, (2) radiation hardness of silicon sensors, (3) low-mass system design, (4) automated precision assembly procedures, and (5) irradiations. Three workshops have been organised in the course of this project: 28 February – 1 March 2013 at

Figure 4: Poster of the Terascale detector workshop 2015.

Mainz University, 6-7 March 2014 at Göttingen University, and 1-3 December 2014 at DESY Hamburg. The following examples may give a flavour of the obtained results.

Within the work package “exchange of experience”, experts from both experiments reported on their experience gained during the development and construction of the current ATLAS and CMS tracking detectors. A list of “lessons learned” was synthesised from these reports and made available to the groups. In a second step, the ongoing activities and plans for the tracker upgrades were confronted with these lessons, such that weaknesses of these developments could be spotted and addressed.

In order to develop sufficiently radiation-hard silicon sensors, both experiments have performed extensive measurement campaigns on test structures and sensor prototypes. Within the PETTL project, the results of these independent measurements have been compared by experts from both experiments. This has resulted in a much improved mutual understanding of these results. The combined results have then been used to improve the models of radiation damage in silicon.

The silicon sensors have to be mounted with a high precision of the order of 10 micrometers in order to achieve the necessary track measurement accuracy. While the mounting structures in the ATLAS and CMS trackers are different, it is very instructive to compare the requirements and the solutions followed in the two experiments. Moreover there has been a collaborative investigation of precise assembly and metrology schemes for silicon sensor modules, and a prototype of a double-sided metrology machine has been built (Fig. 3). Novel gluing techniques have been studied that will allow the assembly rate to be substantially improved.
In summary, the PETTL project was very successful in establishing a fruitful exchange between the groups from the two experiments as well as in strengthening the link between DESY and the university groups. This collaboration will continue beyond the end of Helmholtz funding.

THE TERASCALE ALLIANCE IN NUMBERS

Some key indicators

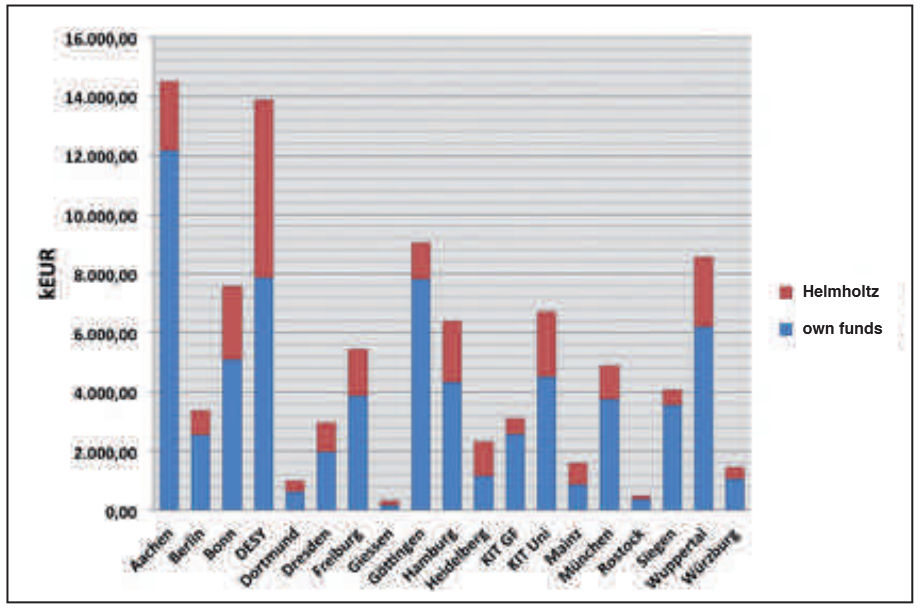


Figure 1: Available Alliance funds (Helmholtz and the partners' own funds) 2007-2014.

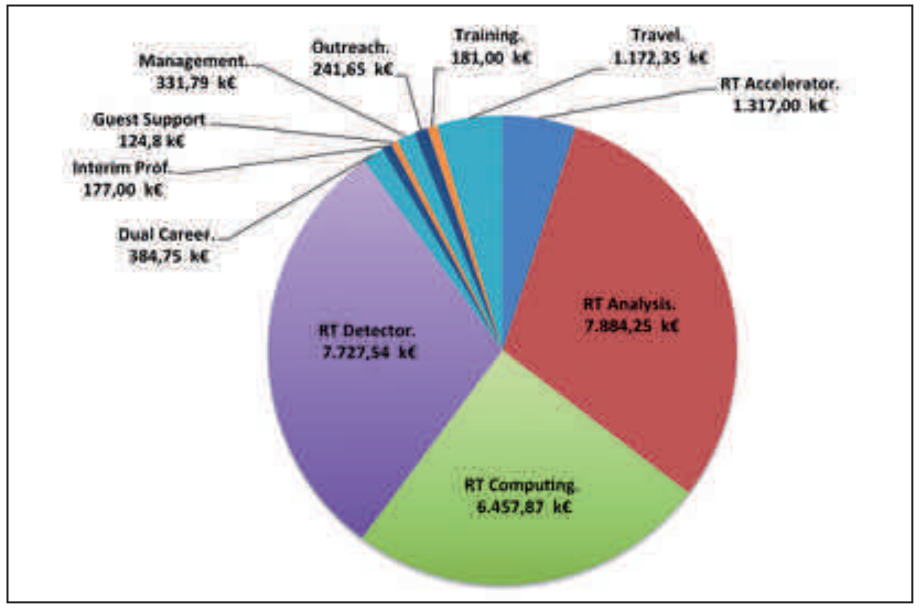
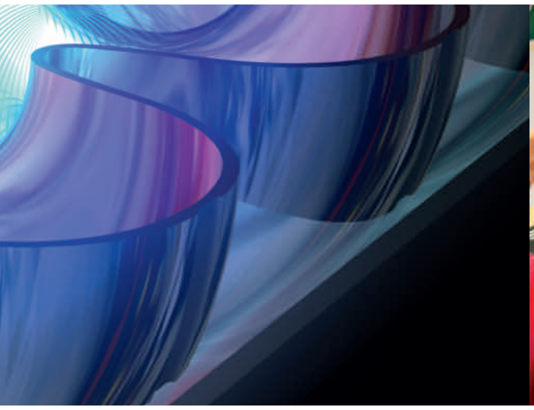
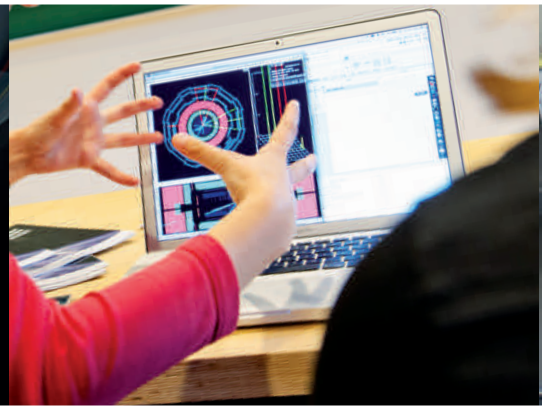
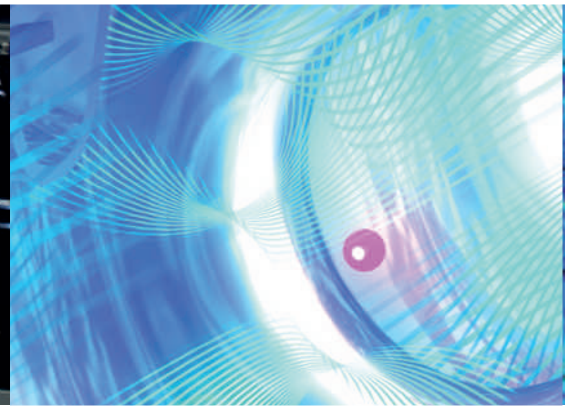
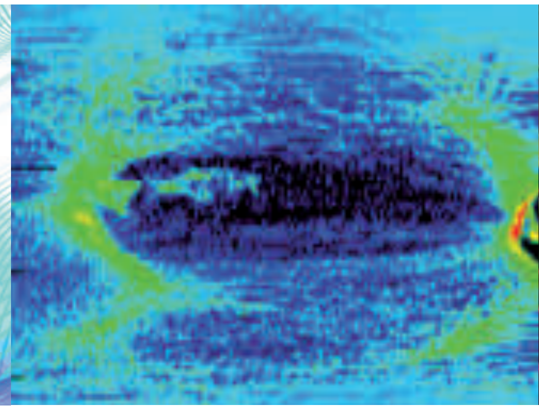


Figure 3: Distribution of Helmholtz funds on the different research topics (RT) and other Alliance activities.

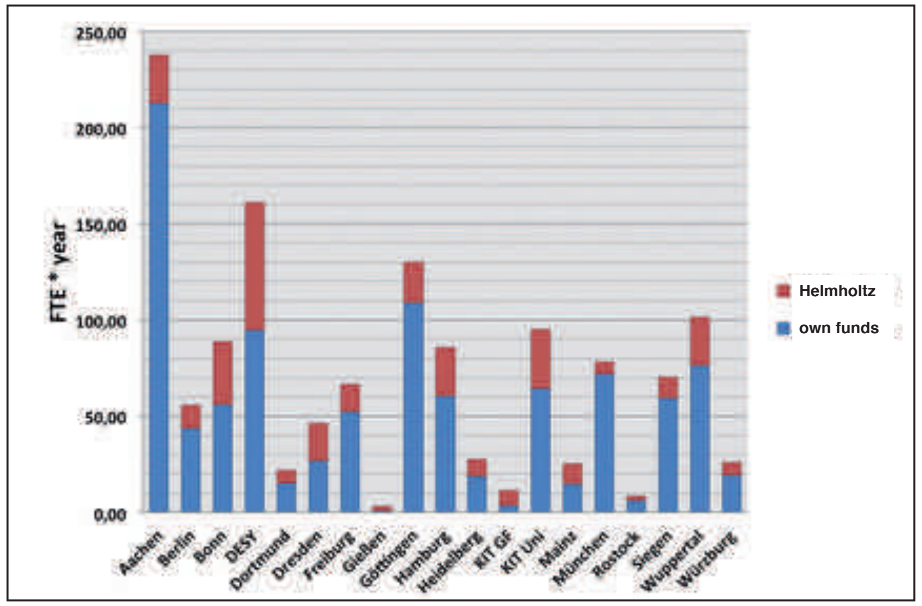



Figure 2: Person years spent within the Alliance, divided in their funding sources.

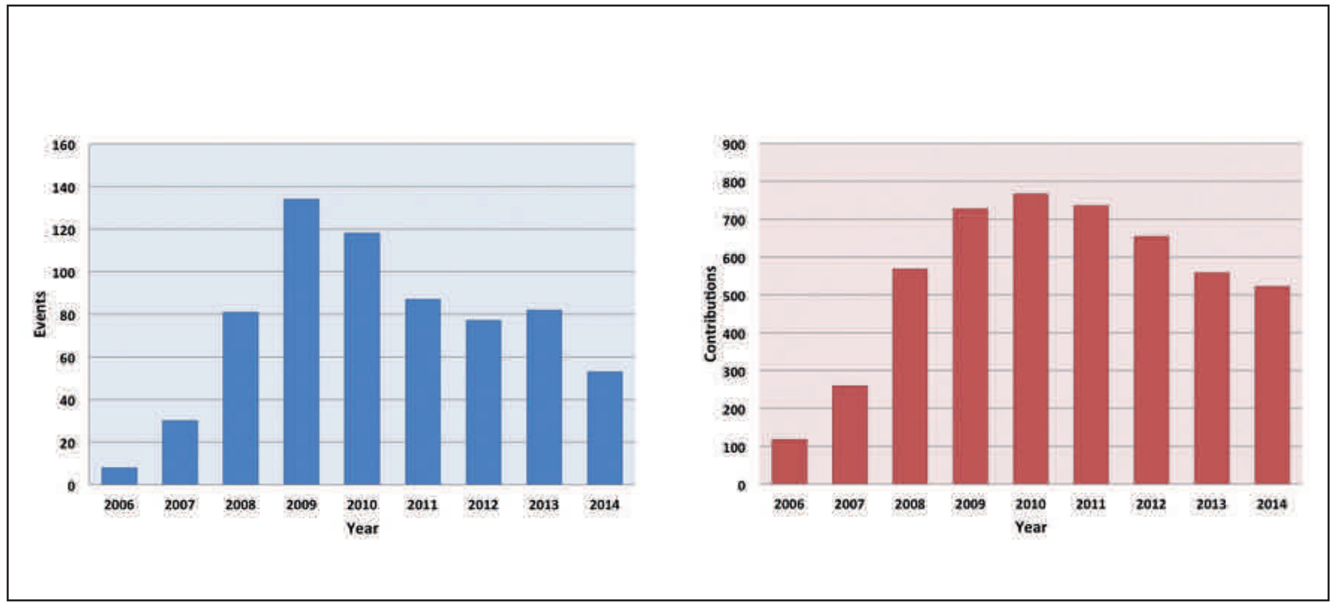
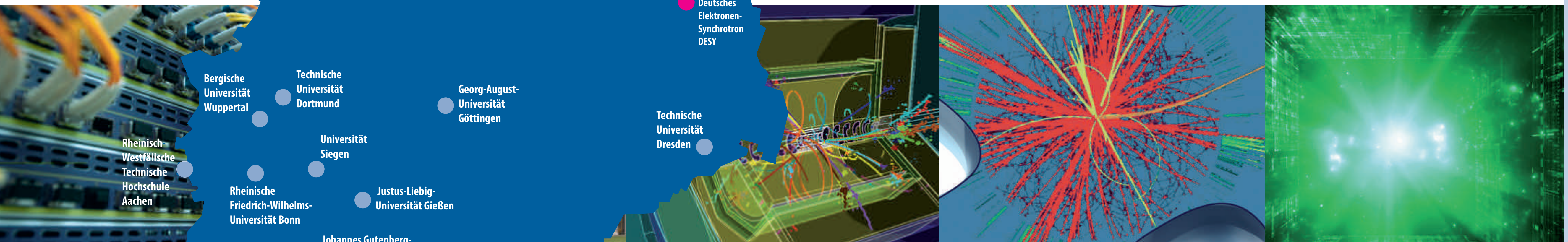


Figure 4: Number of Terascale events per year (left) and number of contributions to these events (right).

THE TERASCALE: AN OVERVIEW

Partner institutes of the Helmholtz Alliance



- 97.6 million Euros total budget, with the Helmholtz Initiative and Networking Fund contributing 26.7 million Euros and Helmholtz partners contributing 70.9 million Euros
- 21 participating universites and research centres
- more than 1000 participating scientists, including about 500 Ph.D. students
- about 50 additional positions financed by Alliance funds
- 5-6 schools per year
- 8-10 workshops per year
- about 225 refereed publications with Alliance relevance per year
- about 80 conference contributions with Alliance relevance per year

THE HELMHOLTZ ALLIANCES

Helmholtz Alliances offer participating scholars and scientists the opportunity to explore new research areas with the necessary critical mass or to further develop current research topics in innovative ways.

Together with several universities and other external partners, the Alliances are organised in associations with international visibility. They are designed as self-managed networks, performing internationally acclaimed research. The Alliances promote young talents and persue stratetic appointment procedures while operating on the basis of an equal opportunity policy. The Helmholtz Association contributes to solving grand challenges which face society, science and industry by performing top-rate research in strategic programmes in the field of Energy, Earth and Environment, Health, Key Technologies, Matter, Aeronautics, Space and Transport.

The Helmholtz Association researches systems of great complexity with large-scale facilities and scientific infrastructure, cooperating closely with national and international partners. The Helmholtz Association contributes to shaping the future by combining research and technology development with perspec-tives for innovative applications and provisions for tommorow's world.

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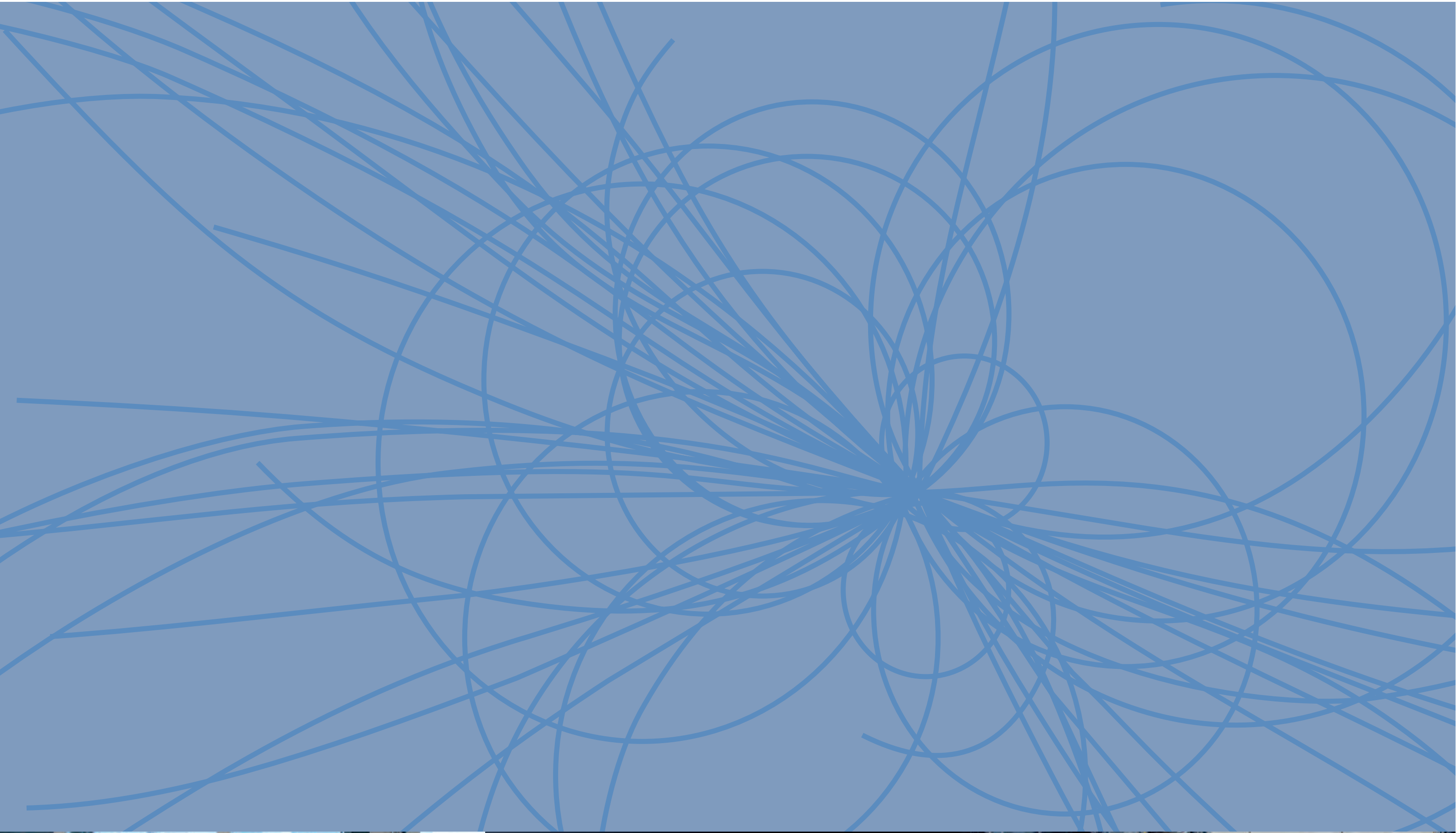

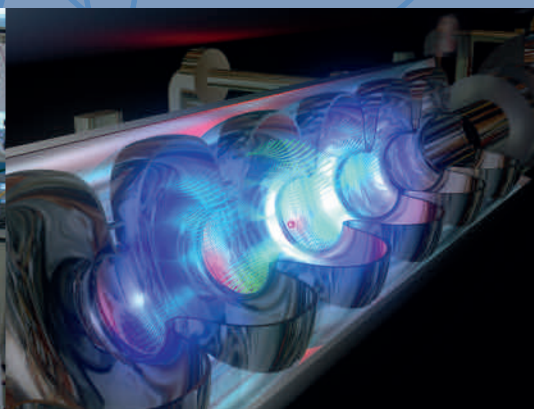

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