Helmholtz-Russia Joint Research Group HRJRG-002
Physics Analysis and Calorimetry at the Terascale

Final Report

Participating Institutes:

Deutsches Elektronen-Synchroton. DESY, Hamburg
Institute for Theoretical and Experimental Physics, ITEP, Moscow
Moscow State University, MSU, Moscow
Moscow Engineering Physics Institute, MEPHI, Moscow

Group Members of the HRJRG:

Principle Investigator (Germany):	Dr. Kerstin Borras (DESY)
Principle Investigator (Russia):	Dr. Roman Mizuk (ITEP)
Group Leaders:	Dr. Felix Sefkow (DESY)
	Prof. Dr. Michael Danilov (ITEP)
	Dr. Michael Merkin (MSU)
	Prof. Dr. Boris Dolgoshein (MEPHI)
Key Researcher:	DESY: 1, ITEP: 1,
Post Doctoral Fellows:	DESY: 2, MSU: 2
Graduate Students:	DESY: 3, ITEP: 1, MEPHI: 1, MSU: 1

The concept of Helmholtz-Russian Joint Research Groups was launched with the primary goal to promote the scientific cooperation with Russia and to provide attractive research conditions for young scientists.
The Helmholtz-Russian Joint Research Group HRJRG-002 was approved in September 2007. The program started on the 1st of November 2007 and ended on the 31st of October 2011. On average the group consisted of 20 members from DESY and the three Russian Institutes.

Description of goals of the group:

The Helmholtz-Russia Joint Research Group HRJRG-002 continued the long-lived and very fruitful cooperation between DESY and Russian Institutes beyond the common efforts for HERA experiments, physics and detector R&D towards new activities at the LHC and for the future LC. Within the project excellent young scientists and students were supported and the possibility for a future career in high energy particle physics was opened for them. All of our young PhD students found an attractive position in international recognized institutes.

The combination of physics and detector activities pursued in this Joint Research Group made the project extraordinary and exceptional. The basis of the project was provided by the profound experience in detector operation and physics analysis collected at HERA. The gained knowledge flowed directly into an imminent project at LHC and provided input to the projects for the future linear collider LC. For this healthy project future prospects were opened by closely relating physics, experiment and the development of novel technologies for the next generation of colliders.

The correct extrapolation of HERA results into the kinematic regime of the LHC needs input of initial data with a special hadron calorimeter in the forward region. Members of the project participated in the construction and operation of this calorimeter, named CASTOR, cultivated skills obtained at HERA and developed further knowledge in detector operation.

One mainstream activity for a detector for a future linear collider involving both DESY and the participating Russian institutes is the development of a hadronic calorimeter. A novel technology was invented in Russia for its readout based on solid state photo-sensors, the so-called SiPM. It is mandatory to strongly pursue its optimization to keep the leading position in this successful development. Beside this novel technology new reconstruction algorithms for hadronic energy deposition were developed and are still optimized employing the test beam data taken in different campaigns at CERN and FNAL.

Thus the activities of the group were centered around the development of experiments in high energy physics from HERA towards the LHC and the LC. The performed HRJRG was tailored to allow efficient participation in this programme by selecting a few important key topics where crucial expertise of participating Helmholtz and Russian institutes were brought in and further developed. Conducting the activities of the HRJRG as originally proposed strengthened the role of the participating Russian institutes and DESY in particle physics . The acquired experience provides the basis for a sustained, long-term participation in fore-front experiments of particle physics.

Developments within the activity areas in the HRJRG-002 group:

HERA & Phenomenology:

The results of HERA on the structure of the proton, the underlying event, multi-parton interactions and dependencies of several QCD processes provide crucial input for searches of new physics phenomena and precision studies at the LHC. The understanding of the HERA results with their consequences for the LHC needed and still do need a strong effort in phenomenology. The studies for the physics analyses, requiring significant computing, were performed at the Tier 2 centers in Russia and at DESY as well as at the National Analysis Facility located at DESY

The analysis of HERA data progressed with a new ansatz for a fit of the proton parton density functions. These new, so-called un-integrated, parton density functions are now employed for simulations of physics processes at the LHC. Just recently the first results of a CMS data analysis on the production of forward jets comparing to these parton densities have been approved for the public by the CMS collaboration.

Phenomenological calculations and studies have been performed for various physics processes at HERA, the Tevatron and the LHC, for example the production of prompt photons and W- and Z- bosons. These processes are most important standard candles in particle physics and are employed to validate the detector performance and calibration. Also the matrix elements for the production of W- and Z-bosons associated with jets and Heavy quarks have been calculated in the kt-factorization scheme, published and implemented into the Monte Carlo generator CASCADE. The work to calculate the production of forward jets and implement them

into the same Monte Carlo generator laid the basis for publishing the above mentioned recent results. The strong activity within phenomenology is proven by the impressively large number of publications with the results produced during the time of this HRJRG-002.

All these efforts in phenomenology build the basis to achieve the goal to develop of a model for the underlying event, multi-parton interactions and the study of possible saturation effects at the LHC

CASTOR & LHC:

The efforts for the forward calorimeter in the CMS Experiment at LHC were pretty exciting and challenging. Only this Helmholtz-Russia Joint Research Group enabled the participation of DESY, MSU and ITEP in this project. The expertise flowing with these group members into the project was well appreciated and acknowledged by the CMS Collaboration, expedited the project considerably and in the end made it possible to be ready just in time albeit its start at a very late stage. Beside the intense construction efforts described below, measurements in test beams have been performed at CERN and published.

In a first installation of a partially equipped half of the calorimeter in 2008 in the CMS experiment it turned out, that the very strong magnetic field of the experiment, with 3.8 Tesla the world-strongest magnet on such a large scale, strayed into the calorimeter area with a strength about 200 times larger than anticipated. Therefore considerable modifications in the mechanics and a drastic change in the kind of Photomultipliers (PMT), the light readout devices, was necessary. PMT's withstanding such a high magnetic stray field are extremely expensive and were out of question within the available budget. A solution was found in re-cycling parts of the PMT's of the SPACAL Calorimeter of the H1 Experiment at HERA, to which DESY meritoriously agreed.
The proposed changes were approved by the management of the CMS Collaboration. With a tremendous effort of all participants finally a fully equipped CASTOR Calorimeter was installed in the CMS Experiment in June 2009. The dedicated contributions to the slow control software by MSU enabled the transition from an expert-operation mode towards the routinely operation by the CMS central shift crew.

Since then the CASTOR Calorimeter takes high quality data and its performance is monitored by the LED system produced by ITEP. Due to the complex behaviour of these special PMT's the calibration turned out to be a very tedious effort. However a first detector performance note has been produced and approved by the CMS Collaboration and been published. Now a first rough calibration is the basis for the presently performed first data analysis of the energy flow in this novel kinematic region. This energy flow will be one first ingredient for the optimizations of hadronic shower models aimed at by the Helmholtz Young Investigator Group of R.Ulrich at KIT, newly approved after the end of this HRJRG. This group is studying high energetic cosmic rays with the Pierre Auger Experiment and needs this input from the LHC for a precise calibration. Its group members are now members of the CASTOR Calorimeter group and participate in and contribute to the future operation. In parallel to all these efforts the test beam measurements of the year 2007 have been finalized and published in a renown journal.

HCAL & LC:

Following the success of the first calorimeter prototype based on SiPMs, which was built by DESY and the Russian partners ITEP and MEPHI, the emphasis in the HRJRG was on consolidating the technology and exploit the data collected at CERN and Fermilab test beams. As a result, the calorimeter performance and simulation were validated, and a detector integration concept was developed which represents a competitive option for a linear collider hadron calorimeter. It is thanks to this effort that the particle flow concept is now considered as being experimentally and technologically established.

The work is performed in the framework of the CALICE collaboration, and in close cooperation with other British, French and German groups. On the analysis frontier, a focus of the DESY activities was to establish the calibration scheme, including the correction procedures, which account for the inherent non-linearities of the SiPMs and for the temperature sensitivity of their gain and response. This lays the ground for all further analyses of hadronic showers, and is an important ingredient for the demonstration of the practical viability of the technology. Another accent was in detailed comparisons of shower topologies with simulations. CALICE data recorded with the scintillator HCAL prototype have already provided important input for the refinement of the modelling of the hadronic cascade.

At ITEP, emphasis was on optimizing the hadronic energy resolution by using weighting methods and exploiting the excellent granularity. One of the most important analyses, the application of state-of-the art particle flow algorithms to test beam data using event mixing techniques, was performed by a young ITEP scientist and is the corner stone of experimental validation of the particle flow approach to calorimetry. All results have been published or entered the publication and review procedures.

On the technology frontier, the challenge lies in the immense channel density, which the particle flow concept requires and which the SiPM allows, but which the electronic and mechanical engineering have to cope with without compromising the performance by dead spaces for cables and pipes or inflating the volume and thereby the cost of the calorimeter and the surrounding solenoid. Advanced mixed-circuit microelectronics read-out chips, which observe the ultra-low power dissipation limits, have been developed in the collaboration, and the DESY group has developed an electronic read-out layer which integrates the photo-sensors, the scintillator tiles, the readout chips and the optical calibration system. A particular difficulty lies in the adaptation of the operational parameters of the electronics to the performance characteristics of the SiPMs and to accommodate the device-to-device variations of their properties, which result from the semiconductor production process. The close cooperation between the Helmholtz and the Russian groups is a unique opportunity to fully optimize the interplay and the potential of these high-tech components.

ITEP focused on the optimization of the SiPM mechanical and electrical characteristics and development of scintillator tile technology suitable for compact design of the layer and mass production. As a result a sensitive detector emerged which matches all challenging requirements.

The read-out layer has been tested in the DESY beam and is now under production for a large-scale prototype calorimeter of the second generation. For this also a

compact and cost-efficient mechanical structure with minimized dead spaces was developed. Thanks to timing the capabilities of the new electronics, it will become possible to study the time evolution of hadronic showers and to test methods of pile-up background rejection, which becomes more relevant in the harsh running conditions of a multi-TeV linear collider, but also at the LHC.

Both ITEP and MEPHI made efforts on further development of the SiPM-scintillator technology. The possibility of the direct coupling of the SiPM to scintillator without a WLS fiber was studied. ITEP tested special geometries of the tile to achieve a uniform light yield over the tile area. MEPHI developed a novel idea of a large area and rectangular shape SiPM that was attached to the tile edge. Both approaches has shown promising results and offer capabilities for further development and optimization

Major achievements of the HRJRG-002 group:

Organization and meetings of the group:

The structure of the HRJRG group was naturally arranged within the different activity areas. Intensive cross talk between them was guaranteed by regular common meetings. The kick-off meeting as well as the final meeting took place in Moscow. The kick-off meeting was dated just before the annual ITEP Winterschool, which offered a very attractive place for fruitful discussions. The final meeting was hosted meritoriously by MSU with a very enjoyable organization. In between of these two special meetings three annual meetings were organized in form of a one day workshop at DESY. In addition students participated in the ITEP Winterschool.

A special highlight was the SiPM workshop organized at DESY, in which 45 registrants from 20 different institutes and 8 countries participated. Physicists, students from different experiments as well as companies reported equally well about their R&D studies and developments. For some members of the HRJRG-002 group this was the first opportunity to participate in an international event. The gathering of international experts was used to tie strings between members of the CALICE Collaboration and the CMS Collaboration, both working for a hadronic calorimeter employing the technology of SiPMs.

Development of the scientific careers of HRJRG-002 members:

In total five PhD students, one from ITEP and four from DESY, finished their work and passed successfully their defence. All have now excellent positions with foreign institutes: one is employed by a US University to work at CERN on the data analysis of the CMS experiment and one pursues phenomenological calculations at the University of Madrid. Another one is now employed as PostDoc at the University of Antwerp, working for the CMS Experiment. The last one had worked at DESY for CALICE with SiPMs He was successful in the application for a DESY PostDoc fellowship and is transferring now his profound experience with SiPMs to the upgrade project in CMS. One PhD student in Russia left for industry, however replacements for him and finally graduated students have been successfully found.

This HRJRG offered two phenomenologists within the group to pursue their studies with a good financial basis, which is usually not the case. They succeeded to publish

their important results in numerous publications, a very good foundation for their future career.

One PostDoc Fellow from DESY accomplished to obtain a position in the analysis center of the Helmholtz Terascale Alliance. During half of his time he is allowed to pursue data analysis in an experiment, which he does within our HRJRG with CASTOR calorimeter data.

On the senior side one key researcher from DESY became spokesman of the CALICE collaboration and the principal investigator at DESY is leading now the whole CMS group at DESY with presently more than 60 members.

On a more private side it has to be emphasized, that with the personal grants this HRJRG opened for three members the possibility to further increase their family life with a new baby, without having to worry about their professional position and further career.

Publications:

In total more than 30 articles were published with the results achieved during this HRJRG-002. About 20 of these articles stem from our members working successfully on phenomenology. Three of those papers are common papers on jointly performed calculations and laying the basis for future precision measurements at the LHC. The remaining papers are published within the CALICE HCAL activity or with the H1 Collaboration and finally one for the CASTOR calorimeter.
In addition several conference contributions were published in proceedings for all activity areas.

Outlook:

In the area of HERA almost all activities envisaged for the duration of this HRJRG-002 have been accomplished and finished.

The members of the HRJRG continue to operate and maintain the CASTOR calorimeter. Partially they are supported by a new Russian fund (non-permanent), dedicated to the forward physics at the LHC. The group members take care for the calibration and analyse the data together.

The group decided to start a common project to work with joined forces for the upgrade of the CMS HCAL with SiPM envisaged for the next LHC upgrade phase.

For an intermediate step third party funding from the Landesexcellence cluster of the University Hamburg and DESY could be acquired successfully. With this money of about 80k Euros the SiPMs for the outer region of the CMS HCAL could be ordered. This outer region of the CMS HCAl needs the upgrade first. Members from our HRJRG-002 institutes, together with the newly joined group of the RWTH Aachen, prepare the replacement of the SiPMs in the central ring of the CMS HCAL Outer.

For the future the start-up of a new group with new young scientists is envisaged. This will enable us to transmit the traditionally excellent relations between DESY and Russian Institutes towards the next generation of young physicists. The main

ingredient would be the CMS HCAL Barrel upgrade in conjunction with SUSY physics at the LHC.

The basic of this effort is the profound competence of the LC HCAL group with SiPMs , therefore also the new group intends to closely pursue the R&D of the LC HCAL.
The possibility of multi-TeV energy offered by CLIC technology for the future LC sets new requirements on the hadronic calorimetry. Members of the HRJRG participate in beam tests with tungsten absorber, development of read-out electronics for more dense HCAL environment and development of fiber-less SiPM-scintillator coupling.

Collection of major Publications:

Phenomenology:

H. Jung, M. Kraemer, A.V. Lipatov, N.P. Zotov, "Heavy Flavour Production at Tevatron and Parton Shower Effects", DESY 10-134 (submitted to JHEP).

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