Final Report

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Participating University:	Universität Hamburg
Report Period:	04/2011 – 09/2016

1) Summary (max. 1 DIN A4 page)

Please describe the main results and the progress achieved in comparison to the state of the art at the time of writing the application and give an outlook on possible future work and applications.

The Young Investigator Group „Higgs Physics with Photons at the ATLAS Experiment“ was part of the ATLAS group at DESY and officially existed from April 2011 until September 2016. The main topic of this Young Investigator group was the search for the Higgs boson in its decay to two photons ($H \rightarrow \gamma\gamma$), complemented by measurements of photon production in proton-proton collisions and contributions to the upgrade of the ATLAS silicon microstrip detector.

During the first years of the YIG, the Large Hadron Collider (LHC) outperformed expectations and the data samples that were collected during 2011 and 2012 were substantially larger than expected. For this reason, the original time plan of the YIG was adapted to focus essentially from the beginning on the Higgs boson search. The YIG made contributions to the preparation of the photon reconstruction used for the 2012 data, the photon identification efficiency measurements, one of the needed inputs for all analyses relying on final states with photons, and the Higgs search itself. In this way, the group was able to make significant contributions to the Higgs boson discovery in summer 2012, for which the $H \rightarrow \gamma\gamma$ decay was one of the main channels. After the discovery, the YIG contributed to the property measurements of the Higgs boson in the $H \rightarrow \gamma\gamma$ channel, including in particular the study of the Higgs boson production processes and the measurements of the fiducial and differential cross sections, published in several conference notes and publications of the ATLAS collaboration. The results of the measurements are consistent with the expectations from the Standard Model of particle physics (SM) within the presently still sizable uncertainties. From 2012 to 2013, I served as the convener of the $H \rightarrow \gamma\gamma$ subgroup within the ATLAS collaboration, and Elisabeth Petit served in the same role during 2015 while being a postdoc in the YIG.

The YIG was consistently involved in the several aspects of the ATLAS electron and photon combined performance group. In addition to the contributions to the photon identification measurements, the combination of the results of the different complementary efficiency measurements, and the photon reconstruction, Marcos Jimenez Belenguer and Elisabeth Petit served as conveners of the photon identification subgroup from 2012 to 2013 and from 2014 to 2015, respectively. I served as convener of the electron and photon combined performance group, in charge of the reconstruction, calibration and identification of electrons and photons, from 2013 to 2015.

I am continuing the work on Higgs measurements and the related photon performance aspects in the context of my ERC Starting Grant and a project in the SFB 676.

Measurements of differential cross sections in events with two photons and jets have been

performed since 2014 and the results are under review by the ATLAS collaboration towards a publication.

The detector-related work focused on two topics. To study the effect of radiation damage in the future detector on the Lorentz angle of the sensors, test sensors were irradiated with neutrons to different fluences. Test beam measurements were performed for non-irradiated and irradiated sensors to study the impact of the radiation damage on the Lorentz angle. These measurements contributed to the technical design report for the future ATLAS silicon strip detector. The re-analysis of the data is currently ongoing together with a new student at DESY with the aim to prepare a publication about the results.

In close collaboration with CNM in Barcelona, microchannel cooling test structures as a possible cooling technology for future silicon detectors have been tested for their fluidmechanical and thermal properties. Results have been published in a paper and continued collaboration with CNM for further studies is planned.

2) Work and Results Report

a) Starting point (max. 1 DIN A4 page)

Please describe the point(s) at issue, the aims and the working hypotheses of the project.

One of the primary goals of the ATLAS experiment was the search for the Higgs boson. Results from the LEP and TeVatron experiments interpreted in the SM suggested that the Higgs boson might be fairly light. For a light Higgs boson, the decay to two photons was expected to be one of the most promising final states for its discovery. Projections expected that about 10 fb^{-1} would be needed to find evidence for the Higgs boson decaying into two photons at the level of 4σ. At the time the proposal was written, a dataset of this size was expected to have been collected by 2014. For this reason, the original plan of the YIG had been to first carry out differential cross section measurements of events with at least one or at least two photons, as a first step towards the search for $H \rightarrow \gamma\gamma$, and then proceed to the $H \rightarrow \gamma\gamma$ search.

The differential cross section measurements of events with at least one or at least two photons are interesting as they provide insights into QCD processes at center-of-mass energies that had not been explored before the LHC. At the same time, the measurements give insights into the backgrounds for $H \rightarrow \gamma\gamma$, which consist mostly of events with two photons and events with one photon and a hadronic jet misidentified as a photon. Both myself and Marcos Jimenez Belenguer, who was a postdoctoral researcher in the YIG, had started to contribute to these measurements with the data collected during 2010 before the starting time of the YIG.

The ATLAS detector will be upgraded for data taking at High Luminosity LHC (HL-LHC) expected to start in 2026. The upgrade includes a replacement of the silicon strip detector, which is needed as the current detector will have reached the end of its lifetime at the time of replacement, and because the expected experimental conditions expected at HL-LHC require a design capable of handling the expected high particle densitities, and a more radiation hard technology. One aim of the YIG was to contribute to the ongoing effort at DESY towards the strip detector upgrade. At the starting time of the YIG it was known from previous studies that the effect of radiation damage on the Lorentz angle of the silicon sensors was not very well understood.

b) **Description of the results (max. 4 DIN A4 pages)**
Please describe the scientific and/or technical success of the group as well as secondary results achieved and essential experience gained. Please classify your own work within the national and international context.

Search for and discovery of the Higgs boson in its decay to two photons
The search for the Higgs boson in its decay to two photons profits from the excellent photon energy resolution, which results in a $H \rightarrow \gamma\gamma$ signal to show up as a narrow peak in the diphoton invariant mass distribution. The background consists mostly of events with two photons produced via nonresonant production (about 75%) and events with one photon and a hadronic jet misidentified as a photon (about 25%). Its diphoton invariant mass distribution is smoothly falling and therefore a $H \rightarrow \gamma\gamma$ signal can be searched for as a narrow peak on top of a smooth background.

During 2011, the ATLAS experiment recorded 4.9 fb^{-1} of *pp* collision data at 7 TeV. With this data, a deviation from the background-only hypothesis of 2.8σ local (1.5σ global when taking into account the look-elsewhere effect) was seen in the diphoton decay channel for m_H = 126 GeV in December 2011. When combined with the results from the ZZ*, WW*, and ττ decay channels, the significance increased to 4.6σ local (2.3σ global). By summer 2012, an additional 5.3 fb^{-1} of *pp* collision data at 8 TeV had been recorded. In the combined analysis of the 7 and 8 TeV data, the deviation from the background-only hypothesis increased to 4.5σ local (3.6σ global) in the diphoton channel. When combined with the results from the ZZ*, WW*, ττ and bb decay channels, the significance reached 5.9σ local (5.1σ global), which allowed to claim the discovery of the new particle. This discovery will remain one of the most important achievements of the LHC.

The main contributions of the YIG to the ATLAS $H \rightarrow \gamma\gamma$ search and discovery were the contributions to the photon reconstruction and the photon identification efficiency measurements (see below), as well as studies of the event categorization for the search, which is introduced to improve the sensitivity by separating events with better and worse expected signal-to-background ratio and better and worse expected invariant mass resolution. At the time of the introduction of the event categorization into the search, it improved the sensitivity by 15%. In addition, I served as one of the editors for the conference note presenting the $H \rightarrow \gamma\gamma$ results that contributed to the Higgs boson discovery in summer 2012.

Property measurements of the Higgs boson in its decay to two photons
After the discovery of the Higgs boson, the focus of the studies in the diphoton decay channel shifted to the measurement of the properties of the Higgs boson to determine whether it does indeed look like the Higgs boson expected in the SM or not. The YIG was involved in measurements of the Higgs boson mass, studies of the production processes and the spin of the Higgs boson, as well as fiducial and differential cross section measurements. Within the present uncertainties, the properties of the Higgs boson are consistent with those expected from the SM.

With the 7 and 8 TeV datasets, the YIG contributed to the event categorization for the study of Higgs boson production in association with a vector boson, and to almost all aspects of the fiducial and differential cross section measurements, contributing to several conference contributions and publications. The product of the Higgs production cross section and the decay branching ratio to two photons is measured with a precision of 23% with the 8 TeV data. The $H \rightarrow \gamma\gamma$ production mode measurements were an important input to the combined Higgs boson coupling fits. In addition to the official ATLAS results, the YIG also performed differential measurements of track-based inclusive event shape variables and studied the performance of these variables for the selection of vector boson fusion events. These studies are documented on doctoral and Masters theses. For the early measurements with the 13 TeV dataset taken in

2015, the YIG contributed to almost all aspects of the fiducial cross section measurements. The production process measurement with the 2015 data and the 2016 data taken up to summer 2016 was coordinated by Nicholas Styles after he joined the analysis as a postdoc in the YIG.

Elisabeth Petit and I served as conveners of the $H \rightarrow \gamma\gamma$/ $H \rightarrow Z\gamma$ subgroup within the ATLAS collaboration (2015 and 2012-2013), contributing to all active searches and measurements during that time.

Other Higgs-related searches and studies

Several other Higgs-related searches and measurements were carried out by the YIG. With the data collected at 7 TeV, a search for a Higgs boson decaying to two light (100-400 MeV), CP-odd scalars decaying into two photons each was performed by the YIG in collaboration with colleagues from CERN and Carleton (Canada). While much of the techniques from the $H \rightarrow \gamma\gamma$ search could be used, the photon identification had to be adapted specifically for this signature. No signal was observed and limits on the production cross section times decay branching ratio were derived.

The YIG contributed to the search for diphoton resonances lighter or heavier than the Higgs boson with the 8 TeV dataset, relying on very similar techniques as the Higgs boson search. The search was carried out in close collaboration with the LAPP Annecy group. No deviation from the background-only expectations were seen and limits were set of the product of the production cross section and the branching ratio into two photons. The YIG also contributed to the search for high-mass resonances decaying to two photons with the 13 TeV dataset taken in 2015. The data were consistent with the expected background. The largest deviation from the background expectation was seen around 750 GeV with a significance of about 2σ after taking into account the look-elsewhere effect. The analysis of larger datasets resolved this deviation to be a background fluctuation.

In addition, contributions were made to the search for di-Higgs production in the final state with two photons and two b-quarks. This analysis was then continued in a different team of the ATLAS DESY group.

Related to the search for Higgs production in association with a top-antitop pair using Higgs decays to two b-quarks, in which another team of the ATLAS DESY group is involved, the YIG contributed to integration of MadGraph5_aMC@NLO into the ATLAS Monte Carlo generator framework, which was then also used to study ttcc production.

Measurement of differential cross sections in events with at least two photons and N jets

Measurements of events with photons in the final state allow for a study of QCD processes. A measurement of differential cross sections in events with at least two photons and N jets has been carried out in collaboration with colleagues from LAPP Annecy (France), Milano (Italy), and Hefei (China). In total, 16 observables describing the diphoton system, the separation between photons and jets, the jets' transverse momenta and the dijet system are measured as a function of the jet multiplicity. Measurements of diphoton variables in inclusive events, i.e. events selected without taking into account the hadronic jets, already existed from the 7 TeV dataset and were already ongoing for the 8 TeV dataset, and adding the study of the jet multiplicity allowed to obtain results not yet available, but very interested for the study of QCD processes. The YIG was involved in almost all aspects of the measurement, and in particular developed a two-dimensional implementation of the unfolding procedure used for the correction of detector resolution effects. In many areas of phase space, the measured differential cross sections are limited by systematic uncertainties related to the subtraction of backgrounds where one of the two photon candidates is a misidentified hadronic jet or the

knowledge of the jet energy measurement. The measurements are compared to several theoretical predictions. The analysis procedure and results are currently under internal review by the ATLAS collaboration.

Photon reconstruction, identification and identification efficiency measurements

An excellent performance of the photon reconstruction and identification, as well as the precise knowledge of the efficiency is an essential ingredient for the analyses described above. The YIG was involved in the preparation of the photon reconstruction for the 8 TeV data. The higher number of *pp* collisions per bunch crossing (referred to as pileup) in the 8 TeV data compared to the 7 TeV data required the adaptation of the reconstruction. Thanks to the improvements, the robustness of the reconstruction was stable with respect to pileup for the experimental conditions in 2012.

During 2011, the YIG developed an existing method for photon identification efficiency measurements into a precision measurement. The method ("electron extrapolation") uses $Z \rightarrow ee$ decays to select a clean, unbiased sample of electrons via the tag-and-probe method. Electrons leave a similar shower in the electromagnetic calorimeter to photons and the remaining differences are corrected for using simulated electrons and photons. The method is now able to measure identification efficiencies with uncertainties at the percent-level. The efficiency measurements with the electron extrapolation were carried out by the YIG for the data taken at 7 and 8 TeV in 2011 and 2012. The results were statistically combined with those of complementary efficiency measurements, an activity that was also performed by the YIG. The small uncertainties achieved benefitted the analyses described above, and also other analyses in ATLAS with photons in the final state.

The YIG further contributed to studies of the photon identification in the 8 TeV data, and was a main contributor to the definition of the photon identification used during 2015 and 2016 for the 13 TeV data in the trigger and in the analyses, used by all ATLAS analyses with photons in the final state. The reoptimization was necessary due to the changes in the experimental conditions, in particular in the pileup. The photon reconstruction was reoptimized for the same reason and the YIG contributed to the validation of the reconstruction used in 2015 and 2016.

The reconstruction and energy calibration of photons relies on a very good simulation of the detector and in particular the detector material. The YIG contributed to studies of the detector material using low energy photons converting into e^+e^- pairs using data taken at 7 TeV in 2010 with low pileup. An precise measurement of the detector material was not possible with this dataset due to biases from the triggers used to collect the events, but many of the techniques developed and lessons learned could be transferred to a measurement performed with data taken in 2015. In addition, the studies with the 2010 data to which the YIG contributed allowed to estimate the size of the dataset that was specifically taken for this next round of studies.

YIG members also contributed to the electron and photon combined performance work within ATLAS in coordinating roles. Marcos Jimenez Belenguer and Elisabeth Petit served as conveners of the photon identification subgroup (2012-2013 and 2014-2015). I served as convener of the electron and photon performance group, coordinating the work related to electron and photon reconstruction, calibration, and identification within the ATLAS experiment (2013-2015).

Future ATLAS silicon strip detector

The ATLAS detector, in particular the subdetectors close to the interaction point, receives considerable radiation doses during *pp* collision data taking. For the future detectors to be installed during the LHC shutdown (planned for 2024-2026) for the HL-LHC, the received radiation doses will be considerably higher. The effect of the irradiation on the detector

performance has to be understood. For silicon detectors, which are installed close to the interaction point, radiation damage results in damage to the silicon itself, causing for example a reduced efficiency and changes to the Lorentz angle in the silicon sensor. These effects have to be taken into account in the signal reconstruction. The YIG used test sensors, some of which were irradiated with neutrons at various fluences ranging from smaller to larger than the fluences expected for HL-LHC, and carried out test beam measurements. The measurements were done in the DESY test beam, using a test beam telescope for the measurement of the tracks placed in a 1 T solenoid magnet, and cooling the test sensors to -25°C. The test sensors were read out with an analogue ALiBaVa system. The data were used to measure the collected signal as a function of the fluence. These measurements are typically performed using radioactive sources and performing these measurements also in the test beam, where the conditions are closer to those in the real detector, is a very valuable check. These measurements contributed to a conference publication. The measurement of the Lorentz angle as a function of fluence proved considerably more difficult and is still ongoing. The first conclusions are that the effect of the (effective) Lorentz angle will be small for the future ATLAS strip detector. The preliminary measurements contributed to the technical design report of the future ATLAS silicon strip detector.

For the powering of the future silicon strip detectors, high-voltage multiplexing is considered to reduce the number of cables needed. In collaboration with colleagues in ATLAS, high-voltage transistors were irradiated at KIT in Karlsruhe and their radiation tolerance was tested. While most of the tested transistors did not conform to the requirements in terms of radiation tolerance, one model was identified as promising candidate. The studies were then followed up by the other groups in Great Britain and the US with which the work was performed and contributed to several conference publications.

Operation and simulation of the ATLAS silicon strip detector

The effects of radiation damage are already a concern for the current ATLAS silicon detectors. The YIG implemented and studied the effect of charge trapping in the sensors in the simulation of the silicon strip detector. It was concluded that no important effects is expected during the running time of the detector until 2023. Another important aspect of the simulation of the silicon strip detector is the simulation of the cross talk. The dependence of the cluster size on the cross talk was studied in the simulation, and the simulation was compared to the data. The studies did not lead to any changes in the nominal simulation. The YIG contributed to the monitoring of the silicon strip detector during the data taking in 2012 and 2013.

Study of microchannel cooling as a technology for future silicon tracking detectors

The cooling of the silicon sensors and the electronics plays an important role for silicon detectors. On the one hand, the cooling systems need to be able to transport the heat produced in the detector, on the other hand, they should add as little as possible material to the detector. One technology under study is cooling through microchannels, where micrometer-sized channels are etched into silicon. Together with CNM Barcelona, a microchannel test structure was designed, fabricated by CNM and simulated and tested by the YIG. The studies include studies of the fluidmechanical properties (including flow, pressure, …) and the thermal properties. Results were presented in a common publication. The test structure is capable of removing the heat produced in a detector module similar to those of the upgraded ATLAS silicon strip detector, and in general the results obtained in the laboratory and from finite element simulations show good agreement, which is useful for further improvements of the design of the cooling structure.

c) **Outlook on future work, sustainability (max. 2 DIN A4 pages)**
Did you encounter unexpected effects or questions during the funding period? Do you see the need for further research in this respect? Please describe planned activities to further develop this work, also if to be carried out elsewhere or in a different constellation.

Most activities of the YIG have continued since the official end of the YIG. The measurements of Higgs boson properties using the Higgs decay to two photons is continued in the context of my ERC Starting Grant and a project in the SFB 676. My ERC Starting Grant project focuses on the measurement of differential cross sections using Higgs boson decays to two photons and will in the future also use Higgs boson decays to four leptons to increase the effective statistical power of the measurements. With the datasets collected over the next years the results will still be limited by their statistical uncertainties. Nevertheless, the uncertainties will decrease by about a factor of three to four (for each channel) compared to the measurements with the 8 TeV dataset and will therefore be a major step forward. The ERC project team is currently contributing to the measurements in the diphoton decay channel with the full 2015+2016 dataset. The project also contains interpretations of the measured differential cross sections in terms of the couplings of Higgs bosons to SM particles and the search for new heavy particles. To support the cross section measurements, the ERC project team is also contributing to the development of the photon identification, the photon identification efficiency measurements, and the electron and photon reconstruction and software. In all these areas, further developments are needed to adapt to the experimental conditions with increasing pileup. The study of the Higgs production processes using Higgs decays to two photons are continued by the SFB project. These measurements will profit from the much increased dataset in a similar way as the differential cross section measurements.

The measurements of differential cross sections in events with at least two photons and N jets are continued with the aim to complete the publication of these measurements.

The analysis of the test beam data is still ongoing to obtain an improved measurement of the (effective) Lorentz angle as a function of the fluence. A new student from the DESY ATLAS group joined this project and works together with the former YIG student, who is still contributing to this effort. The plan is to finalize these measurements for a publication.

I am planning to continue the study of microchannel cooling together with other members of the DESY group and in collaboration with CNM Barcelona. A DESY postdoctoral fellow will probably join the project and we are investigating possibilities for funding to continue the studies.

d) **Potential for application/exploitation (max. 2 DIN A4 pages)**
How do you yourself assess the potential for application or exploitation of the results? Where do you see future possibilities? Please describe realized or planned measures for applying the results. Please also include information on patents, licences, co-operations with industry, etc.

The results obtained by the YIG have high relevance within particle physics, but as research in fundamental physics do not have immediate application in industry. Future measurements will build on the results that the YIG contributed to and techniques developed in the context of this work will continue to be used within the field. The two-dimensional implementation of the unfolding procedure could be developed and tested further to be applicable to arbitrary two-dimensional distributions (at present the second dimension used is the number of jets, and further testing will have to be done to understand the behavior for more general cases). The implementation could then contribute to the root analysis framework, which currently uses the one-dimensional implementation. In the case of the microchannel cooling studies, the design or results might be used by future silicon detectors. Further work is needed to develop the

current design, which focused on a detector element, to a design that could be used in a full detector.

3) Qualification of Junior Researchers (max. 2 DIN A4 pages)
Please describe the structure of the Young Investigators Group in the course of the funding period and the main achievements regarding personal qualifications (including your own): Bachelor, Master; Diploma degrees, conferring of doctorates, "Habilitations", appointments/junior professorships, tenure track, awards, etc. Please also describe any particularities as well as your work-related plans after the end of the funding period.

Between April 2011 and September 2015, three postdocs were part of the YIG team and four DESY fellows were (partially) associated with the YIG for shorter or longer periods of time. Five graduate students completed most of their work towards their theses, and three graduate students were associated or visitors of the YIG for certain periods of time. In addition, one Masters thesis and two Bachelor theses were completed in the context of the YIG.

Marcos Jimenez Belenguer, who was a postdoctoral researchers in the YIG from May 2011 to June 2013, left particle physics research and is now a co-founder and senior data scientist of a start-up focused on machine learning techniques.

Elisabeth Petit, who was a postdoctoral researcher in the YIG from September 2013 to September 2015, now holds a permanent staff position at the Laboratoire de Physique Subatomique & Cosmologie in Grenoble (France).

Nicholas Styles was a postdoctoral researcher in the YIG from October 2015 to November 2015 and then took up a permanent staff position in the DESY ATLAS group.

Yanping Huang was a postdoctoral fellow at DESY from September 2013 to September 2016 and worked closely with the YIG. She now holds a position at the Institute of High Energy Physics in Beijing (China) through a grant from the thousand talents program.

Martin Goebel was associated with the YIG as a DESY postdoctoral fellow from November 2011 to May 2012 and then moved to a position in industry.

Sergei Gleyzer was associated with the YIG as a DESY postdoctoral fellow from May 2012 to October 2014 and then moved to a position in the CMS experiment.

Jike Wang was associated with the YIG rom December 2014 to May 2015 as a DESY postdoctoral fellow and then continued his work in the ATLAS BSM team.

Eda Yildirim was a graduate student in the YIG from November 2011 to January 2016. She has been a postdoctoral researcher in the ATLAS group in Mainz since February 2016. She successfully defended her thesis on "Collected Charge and Lorentz Angle Measurements on Non-irradiated and irradiated ATLAS Silicon Micro-Strip Sensors for the HL-LHC" in December 2016.

Christopher Hengler was a graduate student in the YIG from January 2012 to April 2016 and then moved to a position in industry. He submitted his thesis on the "Measurement of the fiducial differential Higgs cross-section with respect to p_T using the diphoton decay channel at $\sqrt{s}$ = 8 TeV with ATLAS" in January 2017. His defence should take place during the first half of 2017.

Marco Filipuzzi was a graduate student in the YIG from March 2012 onwards. He successfully defended his thesis on the "Measurements of fiducial differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s}$ = 8 TeV with ATLAS" in December 2016.

He is now a postdoctoral researcher at the European Institute of Oncology in Milano (Italy).

Martin Bessner started as a graduate student in the YIG in February 2013. He will be submitting his thesis on the measurement of differential cross sections in events with at least two photons and N jets at $\sqrt{s}$ = 8 TeV and the optimization of the photon identification for trigger and analysis for the $\sqrt{s}$ = 13 TeV data in the next days.

Nils Flaschel started as a graduate student in the YIG in February 2013. He is expected to submit his thesis on the studies of microchannel cooling for silicon detectors and simulation studies for the ATLAS silicon strip detector during the first half of 2017.

Daniel Rauch was a graduate student in the YIG from June 2015 to May 2016. After completing his qualification task for the ATLAS collaboration as part of the YIG, he has continued the work on his thesis in the context of the SFB project.

Cong Peng was a visiting student working closely with the YIG from January to December 2014. He returned to DESY in September 2015 as a joint graduate student at the Institute of High Energy Physics in Beijing and DESY. I am serving as his co-advisor. He worked closely with the YIG (and then the ERC and SFB projects) on the validation of the photon reconstruction for the $\sqrt{s}$ = 13 TeV data and the measurements of fiducial and differential cross sections as well as Higgs production processes in the $\sqrt{s}$ = 13 TeV data. He returned to Beijing in March 2016 and is expected to submit his thesis at the end of 2017.

Phillip Hamnett was a graduate student in the DESY ATLAS group and started to collaborate with the YIG in October 2013 on the studies of photon identification, the optimization of the photon identification for the $\sqrt{s}$ = 13 TeV data and the search for high-mass resonances decaying to two photons with the $\sqrt{s}$ = 13 TeV data. He is now holding a position in industry and should be submitting his thesis soon.

Früd Braren was a Bachelor student in the YIG from October 2011 to June 2012. He successfully defended his Bachelor thesis on the optimization of the photon selection for the search of a Higgs boson decaying to two light, CP-odd scalars in June 2012. He was a Masters student in the YIG from April 2014 to April 2015 and successfully defended his Masters thesis on the “Selection of Vector Boson Fusion Events in the $H \rightarrow \gamma\gamma$ Decay Channel Using an Inclusive Event Shape” in April 2015. He is now a graduate student in my ERC Grant team.

Jens Multhaup was a Bachelor student in the YIG from April to November 2013. He successfully defended his Bachelor thesis on studies on the photon identification and the measurement of differential cross sections in $H \rightarrow \gamma\gamma$ decays in November 2013.

My tenure track evaluation took place in 2014 and I am holding a permanent DESY staff position since August 2014. I received several prizes for contributions to the Higgs boson discovery with my YIG: the Hertha Sponer Prize 2013 of the German Physical Society, the Bjørn H. Wiik-Prize 2012 of DESY, and the IUPAP Young Scientist Prize 2014. As described in 2c I will continue to work on most topics of the YIG.

4) Public relations
By which means did you gain publicity (e.g. reporting in media, own website)?

The YIG was well represented in the ATLAS collaboration and the particle physics community through contributions to publications and conference results, talks at conferences and workshops and convener positions within the ATLAS collaboration.

I have also given lectures at several schools for doctoral students.

Beyond the particle physics community, I have given several public lectures, including in the Augustinum in Hamburg and Aumühle and the Nobelpreistage of the Volkswagenstiftung in Hannover (with Dr. P. Jenni). Together with two colleagues from DESY, I participated in a contribution to re:publica 2013.

In 2014, I participated in the production of a documentary about fundamental physics research, „Die Erkenntnisjäger“ produced by 3SAT (http://www.3sat.de/mediathek/?mode=play&obj=47754). It covers the research at the ATLAS and CMS experiments at LHC and the GEO600 experiment in Hannover.

5) Networking

What co-operation and communication structures (centre/university if applicable) have been developed during the course of the funding? How satisfied are you with the co-operation with the Helmholtz-Centre / university?

The YIG was well-integrated into DESY and the DESY ATLAS group. The analysis activities of the YIG formed one of the four main data analysis topics of the DESY ATLAS group. Similary, the YIG was very well integrated into the ATLAS collaboration, including in particular the Higgs group and electron and photon combined performance group. The ERC Grant team and the SFB project are building on this. The YIG also contributed to the Standard Model photon+jets subgroup and to the silicon strip detector upgrade group.

All students of the YIG were/are students at Hamburg University. The co-operation with both DESY and Hamburg University worked very well.

6) List of Publications

Articles in scientific journals, written contributions to scientific meetings, contributions to books, other publications.

Listed are publications and conference notes to which at least one member of the YIG contributed significantly as part of the YIG project. In addition, the postdoctoral researchers, the graduate students (after completing their qualification period) and I were authors of all publications and conference notes of the ATLAS collaboration.

Journal publications (published or accepted for publication)

- Measurement of the isolated di-photon cross-section in *pp* collisions at √s = 7 TeV with the ATLAS detector. The ATLAS Collaboration. arXiv:1107.0581 [hep-ex]. Phys. Rev. D **85**, 012003 (2012).
- Measurement of the inclusive isolated prompt photon cross-section in *pp* collisions at √s = 7 TeV using 35 pb^{-1} of ATLAS data. The ATLAS Collaboration. arXiv:1108.0253 [hep-ex]. Phys. Lett. B **706**, 150 (2011).
- Search for the Standard Model Higgs boson in the two photon decay channel with the ATLAS detector at the LHC. The ATLAS Collaboration. arXiv:1108.5895 [hep-ex]. Phys. Lett. B **705**, 452 (2011).
- Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb^{-1} of *pp* collisions at √s = 7 TeV with ATLAS. The ATLAS Collaboration. arXiv:1202.1414 [hep-ex]. Phys. Rev. Lett. **108**, 111803 (2012).
- Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. The ATLAS Collaboration. arXiv:1207.7214 [hep-ex]. Phys. Lett. B **716** (2012).

- Measurements of the Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC. The ATLAS Collaboration. arXiv:1307.1427 [hep-ex]. Phys. Lett. B **726**, 88 (2013).
- Evidence for the spin-0 nature of the Higgs boson using ATLAS data. The ATLAS Collaboration. arXiv:1307.1432 [hep-ex]. Phys. Lett. B **726**, 615 (2013).
- Search for the Standard Model Higgs boson decay to a photon and a Z boson in pp collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS detector. The ATLAS Collaboration. arXiv:1402.3051 [hep-ex]. Phys. Lett. B **732**, 8 (2014).
- High voltage multiplexing for the ATLAS Tracker Upgrade. E. G. Villani, P. Phillips, J. Matheson, D. Lynn, L. B. A. Hommels, I.-M. Gregor, M. Bessner, K. Tackmann, F. M. Newcomer, E. Spencer and A. Greenall. JINST **9** (2014) C01032.
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