Final Report

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Project ID No.:	VH-NG-803
Project Title:	Approaching the Fundaments of Physics using Top Quarks at the LHC
Group Leader:	Yvonne Peters
Helmholtz Centre:	DESY Hamburg
Participating University:	The University of Manchester
Report Period:	07/2012-12/2017

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 main focus of the project was the measurement of various properties within the top quark sector with the ATLAS experiment. Furthermore, involvement in the upgrade of the ATLAS detetor for the future high luminosity LHC was ongoing.

During the project, several results were achieved, that were the world's most precise and/or first results. In particular, the first measurement of top quark polarization in top-antitop quark events has been performed; the world's first full exploration of the full spin density matrix in top-antitop quarks was measured; new results on the top quark charge asymmetry, with never-before considered fiducial measurements were achieved; methods were improved to fully reconstruct top-antitop quark events, leading to the first measurement of differential distributions for dileptonic top-antitop quark events with 13 TeV data, including a new measurement of double differential distributions; the group got involved in the search for events of 4 top quarks, with the result being close to publication currently.
Furthermore, during the time of the project, the PI acquired an ERC starting grant to work on colour flow tools and the search for Higgs bosons in association with top quark pairs. The ERC team was based at the University of Manchester, with strong collaboration between both teams (including common tools and meetings).

Besides the work on top quark physics, during the time of the project a strong involvement into a sonar detector control system of the ATLAS detector was ongoing, which lead to new developments and procedures. Furthermore, group members were involved in studying the service layout for the tracker in the future ATLAS upgrade. Another important study was performed integrating Lorentz-angle measurements into the calibration loop oft he SCT, which can be used for monitoring of radiation damage. At the time of writing, one of my PhDs student is still working at DESY, studying the performance of CMOS sensors for radiation-hard tracking detectors.

The achieved results all were new results, requiring the developments and improvement of new tools. For example, the top event reconstruction was improved significantly, helping more than just the results achieved as part of this project. Furthermore, the measurement of unfolded (detector-corrected) distributions in fiducial regions was established in the top sector, which allows the theory community to use the results for model-independent searches.

Future work will build on these achievements, in particular using established methods to acquire improved results with the ever-increasing data sample. As several of the

measurements were limited by the data statistics, more precise results will be expected.

In conclusion, the YIG was a great success, leading to many new results and tools. Furthermore, PhD students and summer students were trained and several postdocs associated with the group acquired leading positions within the ATLAS collaboration (for example C. Deterre: top properties convener). Overall, the achievements reached during the 5.5 years of the YIG running time exceed the original goals by far!

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.

When we started in 2012, ATLAS data collection was still in its early stages. The beam energies had not reached yet their full potential, and the amount of data was much smaller compared to current data. Furthermore, the top quark physics programme was much less advanced than it is now. In particular, precision measurements of differential distributions in dileptonic top antitop quark events were only slowly becoming accessible.
The aims of the projects were to advance the precision measurements, in particular on polarization, spin correlations and charge asymmetries in the top quark sector further. In addition, searches for new particles in the top sector were aimed at, as the top quark is a prominent window to new physics due to it being the heaviest known elementary particle. Furthermore, preparation for the future ATLAS upgrade (in 2023) were aimed at, which at the point of the start of the YIG still required a lot of studies on the design.

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.

Top Physics:

The studies in the top sector started with the analyses of the top-antitop quark (ttbar) charge asymmetry, ttbar spin correlations and top polarization using 7 TeV ATLAS data. These results were published during 2013 and 2014. Several aspects were novel on these results already. For example, the measurement of the top polarization in ttbar events was the world's first published measurement of this quantity.

Based on these initial measurements and the achieved results, the next step was the study of such quantities in 8 TeV data, with improved methods. The measurement of the full spin density matrix in ttbar events was performed for the very first time. For this analysis, the observables were constructed in cooperation with theorists (in particular W. Bernreuther). The observables were all corrected for detector effects, providing distributions usable for the full community. Furthermore, an advanced study of the ttbar charge asymmetry, including various differential measurements (for example the charge asymmetry in bins of different ttbar invariant masses), was performed. Both of these analyses were published during the course of the project, and presented at various international conferences.

Afterwards, the study of 13TeV took place. In particular, my team performed the first analysis of the new 13TeV data in 2015, providing the world's first ttbar cross section measurement at this centre of mass energy. The next step was to perform differential, detector-corrected measurements of observables in the ttbar sector using dileptonic ttbar events. This got published during the course of the project, providing a full set of observables that are usable for new physics searches and to improve the modelling of ttbar

simulation. The modelling of the ttbar events is a major source of systematic uncertainty in many top measurements and searches which have a large ttbar background. Thus, having measured these differential distributions that show sensitivity to the ttbar modelling is highly valuable for the full community. In the final step, double-differential ttbar cross sections were measured, using the largest set of 13TeV data we had available. This analysis got finished and was written up in the thesis of one of the PhD students (Abigail O'Rourke). The publication of this result is still under way.
In parallel, part of the team got involved in the search for 4top events. This class of events is promising for various searches of new physics, as for example vector-like quarks. We used same-sign dilepton final states, which have a low background, but also a small branching fraction. Especially the modelling of the "fake lepton" background is challenging. This analysis got finished, but publication is still under way.

In parallel to the results listed, which were the main focus of the YIG, I ran an ERC team in Manchester, which closely collaborated with my YIG. Several tools and methods were shared between both efforts. On this side, another couple of results indirectly benefited from the YIG funding via direct collaboration of my team members, as for example the first measurement of colour flow using jet pull in ttbar events, or the first evidence for ttH.

Overall, the amount of publications and results we could achieve during the course of the project exceeds the initial goal by far. Some adjustments on the path were done, for example instead of semileptonic events we used dileptonic events for ttbar spin correlations, which have shown to be much cleaner, yielding higher sensitivity. Also the search was adjusted, performing the search for 4top instead of a ttbar resonance search. Besides the 4top process being much more promising for new physics under the current circumstances, the search for wide ttbar resonances was indirectly covered by the measurement of differential ttbar distributions, where we included a measurement of the invariant ttbar mass – which is the observable used for resonance searches. All achieved results were shown at international conferences, either by my team members or by other CMS or ATLAS colleagues.

Given the large success our team had, several team members got important positions within ATLAS, as for example as top properties or ttbar cross section conveners.

In addition to the direct results, several team members were either member or chair of ATLAS-internal Editorial Boards, reviewing further top-related analyses on their way to publication.

Sonar DCS and Lorentz angle:

Several efforts were going into operation – or improvement of operation – of the current ATLAS detector. One PhD student (R. Naranjo) studied the integration of a Lorentz Angle measurement into the SCT calibration loop. The Lorentz angle is expected to change when tracker modules are affected by radiation. A change in the angle thus can help to calibrate the detector signals more optimally.

A larger effort of team members went into the sonar detector control system (DCS). The sonar DCS is used in order to check the gas flow through certain detector parts, and the gas mix. The system required quite some effort in redesigning the software and installing new pieces. Over the course of the project, team members were central to this effort. For example, PhD student Abigail O'Rourke designed a new monitoring tool which is used during online data taking in the ATLAS control room. Several publications were coming out of this effort, besides its direct impact into ATLAS operation.

In addition to all these activities, all members of the team took either ATLAS control room or remote control shifts for data taking.

ATLAS Upgrade Studies:

One of the team members (Cecile Deterre) did a performance study of a cluster splitting algorithm for the ATLAS upgrade of the Pixel detector in 2013. The studies were integral part of testing the design of the ATLAS pixel detector for the future upgrade.
Another team member (PhD student Ralph Schaefer) studied the service routing for the tracking system. In particular, he tested the "default" layout versus an alternative layout in order to see how the performance of the tracking would be affected by the two choices.

Furthermore, PhD student Tom Daubney worked on improving the EUTelescope software and provided assistance for test beam studies at DESY. The EUTelescope is used for studying detector parts in a test beam, allowing to study its performance under real conditions without having to have a full detector assembled. This is important for ATLAS upgrade studies of several parts of the detector.

CMOS Sensors:

Together with a colleague at DESY, PhD student Tom Daublney worked on setting up a test stand to test CMOS chips. Those were proposed as an alternative, cheaper possibility for the tracker upgrade. Over the course of the project, it was clear though that 1. The CMOS technology would not be chosen for the SCT tracker upgrade (due to timing constraints mainly) and 2. That the main two designs had major flaws. The project thus got changed into testing ALPINE chips, which are possible CMOS chips for future detectors – for example for the ALICE detector at CERN. These studies are still ongoing.

Other:

Besides the physics results and technical contributions, all team members benefitted from various trainings. In particular, each team member got the opportunity to go to conferences and workshops, with everyone presenting results at an international conference at least once. This made my YIG visible at the national and international level.
The involved postdocs all got leading positions within ATLAS (for example top properties convenerships), providing them with valuable leadership training. Every team member had been involved in at least one outreach event (open days, talks to schools, public talks..), being another important skill to learn. Each team member took on a summer student at DESY at least once, allowing to train how to supervise students.
Myself (the PI), I have done a lot of different teaching at Universities, in particular Goettingen and then Manchester, as well as lectures at physics schools. My teaching involved various lectures, tutorials, example classes, MPhys students and BSc students. I accomplished two teaching certificates during the time of the YIG (a "Zertifikat fuer Hochschullehre" in Goettingen and a "New Academics Programme" in Manchester). Furthermore, I took on positions like PG coordinator in Manchester's particle physics group for 2 years and became Academic Exchange Advisor for the whole School of Physics and Astronomy in Manchester, thus integrating myself into the University's 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.

The results we achieved are so far all compatible with the standard model prediction. Nonetheless, the results, and in particular the tool developments, are highly valuable for the ongoing physics programme in ATLAS. I plan to expand on the project with my current position at The University of Manchester. In particular, I currently work on using the event reconstruction tools and applying them to events with Higgs bosons produced in association with top quark pairs. I still have one year of ERC funding ongoing, and recently applied for the ERC CG, trying to secure further funding to go on with the research in the top-Higgs sector.

The work done during the funding period of the Helmholtz Young Investigator group builds a basis for many of the future directions. In particular, the established event reconstruction is used in several areas, including my currently ongoing own research. The results achieved on spin correlations and differential distributions are highly valuable to the theory community and for Monte Carlo tuning, which has an impact on the sensitivity achievable in future ATLAS analyses.

The studies undertaken on detector development for the future ATLAS upgrade (during Run II) as well as the work done on the sonar detector control system for ATLAS operation are all inputs to the future design of ATLAS or are used for the current running. The study still ongoing with one PhD student at DESY (Tom Daubney) on CMOS sensors will last at least until end of 2018, expected to provide further insight into the suitability of monolithic sensors for particle physics applications.

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 themselves are not applicable for industrial purposes. The methods though, studying big data, can potentially be used for different areas. I recently got involved into a small project to try to apply analysis methods from particle physics for radiotherapy purposes, in particular for cancer patient registry. The project is only a small-seed fund project, with the aim to explore the feasibility of the methods. This is based in the UK, under the umbrella of STFC global challenge network funding.

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.

During the time of the project 2 PhD students graduated (with 2 more to follow soon – the delay in their PhD was caused by health issues).
Several summer interns were trained during the project, several of which went on with PhDs in particle physics.
Several of the postdocs got ATLAS-internal leadership positions, training their skills for their future career.
Since the university partner was changed from the University of Goettingen to the University of Manchester, Bachelor and Master students were not based at DESY, but instead in Manchester, some of which being involved in projects together with my DESY team.
Myself, I got a permanent position at The University of Manchester, after winning an ERC starting grant. During the time of the project, in which I started as fixed-term Juniorprofessor, I first became Senior Research Fellow (eq. W2 in Germany) at The University of Manchester, and then became Reader in 2016. In 2013, I finished a certificate for higher education teaching

in Goettingen, and completed a “new academics programme” in 2015 in Manchester, leading to me becoming a Fellow of the Higher Education Academy.

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

During the time of the project, several team members participated in outreach events. This included DESY open days, talks to the general public (e.g. at the Nacht des Wissens in Goettingen in 2012, to School kids, etc).
I have my own web page, presenting talks and results: www.hep.manchester.ac.uk/~peters

All team members presented their work at national and international conferences to the particle physics community.

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 full team networked with many international groups, working within international analyses teams within ATLAS, as is standard for our research field.
During the time of the project, several changes happened. After about a year, I switched from the University of Goettingen to Manchester. Besides the better position in Manchester, the cooperation with Goettingen did not work at all, allowing no freedom to do my own research. The cooperation between my team at DESY and the University of Manchester worked well, with the DESY ATLAS group being able to attract several new PhD students and DESY fellows due to this connection.

The cooperation with and integration into the Helmholtz centre initially worked well, although over time several incidents and changes happened that made the situation more and more negative. Several of these incidents were borderline unprofessional. Since this is a public report I prefer to not discuss the details of these issues here, but would prefer to discuss them in direct communication with Helmholtz.

6) List of Publications
Articles in scientific journals, written contributions to scientific meetings, contributions to books, other publications.

1) R. Bates et al., “A combined ultrasonic flow meter and binary vapour mixture analyzer for the ATLAS silicon tracker”, 2013_JINST_8_P02006.

2) V. M. Abazov et al. [D0 Collaboration], “Measurement of Leptonic Asymmetries and Top Quark Polarization in ttbar Production", Phys. Rev. D 87, 011103 (2013).

3) Y. Peters, Proceedings on “Top anti-top Asymmetries at the Tevatron and the LHC", PIC2012, Strbske Pleso, Slovakia, September 2012 [arXiv:1211.6028[hep-ex]].

4) Y. Peters, Proceedings on “ttbar Spin Correlations at D0”, ICHEP2012, Melbourne, Australia, July 2012 [arXiv:1210.7189[hep-ex]].

5) Y. Peters, Proceedings on “Single Top Quark Production at the Tevatron", ICHEP2012, Melbourne, Australia, July 2012 [arXiv:1210.7188[hep-ex]].

6) The ATLAS Collaboration, “Measurement of top quark polarisation in ttbar events with the ATLAS detector in proton-proton collisions at sqrt= 7 TeV", ATLAS-CONF-2012-133, September 2012.

7) The CDF and D0 Collaborations, “Combination of the ttbar production cross section measurements from the Tevatron Collider", D0note 6363-CONF, September 2012.

8) F. Deliot, Y. Peters and V. Sorin, “Top Quark Physics at the Tevatron”, Int. J. Mod. Phys. A 28, 1330013 (2013).

9) S. Borroni, Proceedings on “Measurement of top quark polarisation with the ATLAS experiment”, LHCP, Barcelona, Spain, Mai 2013, EPJ Web of Conferences 60, 20015 (2013).

10) C. Deterre et al., Proceedings on “A custom on-line ultrasonic gas mixture analyzer with simultaneous flowmetry developed for use in the LHC-ATLAS experiment“, ANIMMA, Marseille, France, June 2013, submitted to Transactions on Nuclear Science.

11) The ATLAS collaboration, “Measurement of top quark polarization in top-antitop events from proton-proton collisions at sqrt(s) = 7 TeV using the ATLAS detector”, Phys. Rev. Lett. 111, 232002 (2013).

12) Y. Peters, Proceedings on “Top Quark Mass Measurements at the Tevatron”, EPS2013, Stockholm, Sweden, July 2013 (arXiv:1309.5783[hep-ex]).

13) S. Adomeit and Y. Peters, Proceedings on “V+jets Background and Systematic Uncertainties in Top Quark Analyses”, Top2013, Durbach, Germany, September 2013 (arXiv:1311.7305[hep-ex]).

14) Ralph Schäfer, Proceedings on “Measurement of top quark polarization in dileptonic top-antitop quark events using the ATLAS detector”, Top2013, Durbach, Germany, September 2013.

15) The ATLAS collaboration, “Measurements of spin correlation in top-antitop quark events from proton-proton collisions at sqrt(s)= 7 TeV using the ATLAS detector”, ATLAS-CONF-2013-101, September 2013.

16) T. Aaltonen et al. [CDF and D0 collaborations], “Combination of measurements of the top-quark pair production cross section from the Tevatron Collider”, Phys.Rev. D 89, 072001 (2014).

17) The ATLAS collaboration, ``Measurements of spin correlation in top-antitop quark events from proton-proton collisions at sqrt(s)=7 TeV using the ATLAS detector'', Phys. Rev. D. 90, 112016 (2014).

18) Y. Peters, Proceedings on “Tevatron Top-Quark Combinations and World Top-Quark Mass Combination'', Top2014, Cannes, France, October 2014 (arXiv:1411.0820 [hep-ex]).

19) Y. Peters, Proceedings on ``Top Quark Studies at D0'', BEACH2014, Birmingham, England, July 2014 (arXiv:1408.2257[hep-ex]).

20) R. Baites et al., „A Custom Online Ultrasonic Gas Mixture Analyzer With Simultaneous Flowmetry, Developed for the Upgraded Evaporative Cooling System of the ATLAS

Silicon Tracker“,IEEE TNS, vol. 61, pp. 2059- 2065 (2014).

21) C. Deterre and L. Mijovic, Proceedings on „Measurement of the charge asymmetry in dileptonic ttbar events with the ATLAS detector at sqrt(s)=7 TeV“, Top2014, Cannes, France, October 2014 (arXiv:1412.0570[hep-ex]).

22) R. Schäfer, Proceedings on “Top quark pair properties - spin correlations, top quark pair asymmetry and complex final states using the ATLAS detector at the LHC“, DIS, Warschau, Poland, April 2014, PoS(DIS2014)145.

23) R. Naranjo, Proceedings on “Top Physics in ALTAS”, on behalf of the ATLAS collaboration, Lomonosov conference, Moscow, January 2016, [arXiv:1603.06203 [hep-ex]].

24) ATLAS Collaboration, “Measurement of colour flow with the jet pull angle in ttbar events using the ATLAS detector at sqrt(s)=8 TeV", Phys. Lett. B. 750, 475-493 (2015).

25) ATLAS Collaboration, “``Measurement of the charge asymmetry in dileptonic decays of top quark pairs in pp collisions at sqrt(s)=7 TeV using the ATLAS detector", JHEP 05, 061 (2015).

26) ATLAS Collaboration, ``Measurements of the ttbar production cross-section in the dilepton and lepton-plus-jets channels and of the ratio of the ttbar and Z boson cross-sections in pp collisions at 13 TeV with the ATLAS detector”, ATLAS-CONF-2015-049, September 2015.

27) C. Deterre, Proceedings on “Top mass measurements at the Tevatron“, on behalf of the CDF and D0 Collaboration, Ischia, Italy, September 2015, PoS(TOP2015)036.

28) Y. Peters, Proceedings on ``Top Quark Pair Production Cross Section at the Tevatron", on behalf of the D0 and CDF collaborations, EPS2015, Vienna, Austria, July 2015, [arXiv:1509.07629 [hep-ex]].

29) ATLAS Collaboration, ``Measurement of the ttbar production cross-section in pp collisions at 13 TeV using emu events with b-tagged jets", ATLAS-CONF-2015-033, July 2015.

30) ATLAS Collaboration, ``Event Kinematic Distributions in Top-Quark Enriched Samples from 13 TeV pp Collisions in the ATLAS Detector", ATL-COM-PHYS-2015-612, July 2015.

31) Y. Peters, proceedings on ``Recent Results of Top Quark Physics from the Tevatron", onbehalf of the D0 and CDF collaborations, Rencontres de Blois, Blois, France, June 2015, [arXiv:1507.02422 [hep-ex]].

32) M. Alhroob et al., „Development of a custom on-line ultrasonic vapour analyzer and flow meter for the ATLAS inner detector, with application to Cherenkov and gaseous charged particle detectors**“,** JINST 10 (2015) no.03, C03045.

33) ATLAS Collaboration, “Measurements of top quark spin observables in $t\bar{t}$ events using dilepton final states in $\sqrt{s}$=8 TeV pp collisions with the ATLAS detector”, JHEP 03, 113 (2017)

34) ATLAS Collaboration, “Measurements of the charge asymmetry in top-quark pair production in the dilepton final state at $\sqrt{s}$=8 TeV with the ATLAS detector”, Phys. Rev.

D94 (2016) 032006.

35) ATLAS Collaboration, “Measurements of top quark spin observables in $t\bar{t}$ events using dilepton final states at √s=8 TeV with the ATLAS detector”, ATLAS-CONF-2016-099 (2016).

36) ATLAS Collaboration, “Measurements of top quark spin observables in ttbar events using dilepton final states at 8 TeV with the ATLAS detector”, ATLAS-CONF-2016-099.

37) ATLAS Collaboration, “Search for new physics using events with b-jets and a pair of same charge leptons in 3.2 fb-1 of pp collisions at √s=13 TeV with the ATLAS detector”, ATLAS-COM-CONF-2016-036 (2016)

38) Cecile Deterre, “Why stop at two tops? Search for exotic production of top quarks in final states with same-sign leptons and b-jets at 13 TeV”, on behalf of the ATLAS Collaboration. Proceedings of a poster presented at TOP2016 to be published in eCONF [arXiv:1611.06767].

39) ATLAS Collaboration, “Measurements of top-quark pair differential cross-sections in the electron-muon channel in pp collisions at sqrt(s)=13$ TeV using the ATLAS detector”, (TOPQ-2016-04), Eur. Phys. J. C 77, 299 (2017).

40) Roger Naranjo, “Measurements of the charge asymmetry in top-quark pair production in the dilepton final state at sqrt(s)=8 TeV with the ATLAS detector”, proceings, arxiv:1701.01275.

41) ATLAS Collaboration, ``Search for the Standard Model Higgs boson produced in association with top quarks and decaying into a b-bbar pair in pp collisions at sqrt(s)=13 TeV with the ATLAS detector”, ATLAS-CONF-2016-080, August 2016.

42) ATLAS Collaboration, ``Combination of the searches for Higgs boson production in association with top quarks gammagamma, multilepton, and b-bbar decay channels at sqrt(s)=13 TeV with the ATLAS Detector'', ATLAS-CONF-2016-068, August 2016.

43) ATLAS Collaboration, ``Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at sqrt(s)=13 TeV using the ATLAS detector'', ATLAS-CONF-2016-040, August 2016.

44) ATLAS Collaboration, ``Search for the Standard Model Higgs boson produced in association with top quarks and decaying into a bbbar pair in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector'', arXiv:1712.08895. (submitted to Phys. Rev. D).

45) ATLAS Collaboration, ``Measurement of colour flow in ttbar events using the ATLAS detector at sqrt(s) = 13 TeV'', ATLAS-CONF-2017-069, (2017).

46) M. Alhroob et al., „Custom real-time ultrasonic instrumentation for simultaneous mixture and flow analysis of binary gases in the CERN ATLAS experiment“, Nucl.Instrum.Meth. A845 (2017) 273-277.

47) M. Alhroob et al., „Custom ultrasonic instrumentation for flow measurement and real-time binary gas analysis in the CERN ATLAS experiment“, JINST 12 (2017) no.01, C01091.

Further publications are in progress, in particular the analysis of 4top events and the double differential cross sections.