Annual Report

Funding Programme:	Helmholtz Young Investigators Groups
Project ID No.:	VH-NG-1004
Project Title:	Ultimate precision measurements and searches for new physics using top quarks at the CMS experiment at the LHC
Group Leader:	Dr. Maria Aldaya Martin
Helmholtz Centre:	DESY
Participating University:	Karlsruhe Institute of Technology (KIT, University Sector), Hamburg
Report Period (=Calendar Year):	01/2016-12/2016

1) Group Structure

Please report briefly on the structure and personnel development of your group.

The YIG consists of the group leader and the following members:

Post-doctoral researchers:
- Dr. Carmen Diez Pardos (started 01.04.2014)
- Dr. Johannes Hauk (01.12.2015 – 30.06.2017, on parental leave from 13.04.2016 to 12.11.2016)
- Dr. James Keaveney (started 15.01.2016)
- Dr. Jasone Garay Garcia (01.09.2016 – 30.11.16)
- 2 DESY Fellows have joined the YIG (since January 2016) to work on the tt+H analysis for 30% of their time

PhD students:
- Mr. Mykola Savitskyi (started 01.09.2014, University of Hamburg)
- Mr. Karim El Morabit (started 01.12.2015, KIT)

Comments:

- Dr. Garay Garcia was working during the last 6 months of her PhD in close collaboration with the YIG. After she defended her thesis, she has been employed by the YIG for a total of 3 months to work on the tt+H analysis.

- Mr. Andrej Saibel will start as a PhD student enrolled in the University of Hamburg on 15.02.17.

2) Network

Please describe how you / your research group are integrated within the Helmholtz Centre and the partner university (e.g. as member of committees).

The Young Investigator Group (YIG) is well integrated in the High Energy Physics department of DESY, in particular the CMS group, and contributes significantly to the research program of the Centre. Close cooperation between the YIG and the corresponding working groups in the fields of top quark physics, Higgs physics, and CMS tracker upgrade both at DESY and partner universities is well established.

Responsibilities of the YIG members within DESY and partner universities (alphabetically ordered)**:**

Dr. M. Aldaya
- Since 2016 Elected member of the DESY Scientific Committee (WA).
- Since 2015 Administrative leader of the DESY CMS group CMS-F (composed of subgroups CMS-F1, CMS-F2, CMS-F3), in which the CMS Top Quark Physics research activity at DESY is carried out; leader of CMS-F1.
- Since 2015 Associated scientist in the Karlsruhe Research Training Group GRK 1694: *Elementarteilchenphysik bei höchster Energie und höchster Präzision* (Graduiertenkolleg).
- Since 2014 Convenor of the DESY-CMS Top Quark Physics Group at DESY Hamburg (as of Dec 2016: about 20 scientists, including all YIG members), initiating and coordinating the analyses carried out by the group, and guiding the work of the PhD students and post-doctoral researchers.

Dr. C. Diez Pardos
- Since 2014 Coordinator of the working meetings of the DESY-CMS Top Quark Physics Group at DESY Hamburg.

Dr. J. Keaveney
- Since 2016 Leader at DESY of the development of automated module assembly and metrology system for the detector modules of the CMS tracker for HL-LHC.

3) Satisfaction
How satisfied are you with the general working conditions provided by the Helmholtz Centre / partner university? Is there anything that meets your criticism?

DESY offers the perfect infrastructure for international research. The support of the Centre and the partner universities corresponds to the cooperation contract.

4) Scientific Progress / Milestones
How has your work plan progressed? Which important milestones could be achieved during the report period? Is the progress of your work in accordance with original planning or has the work plan been changed?

The activities of the group are divided into several working packages that address the different topics described in the project: precision measurements of top quark pair (tt) production at CMS and the LHC, the measurement of tt production in association with a Higgs boson (tt+H) and its main background processes at CMS, and the investigation and participation in novel design options for the next CMS tracking detector. The work plan is progressing in accordance with the original planning.
In the following, the progress of each of the working packages is summarized.

Precision measurements of inclusive and differential top quark pair (tt) production at CMS and combination of results from the CMS and ATLAS Collaborations

The group is well established as key player in the Top Quark Physics Analysis Group of the CMS experiment. The YIG is contributing strongly to the most precise measurements from the Run-I of the LHC ("LHC Run-I legacy") in CMS, as well as to the first measurements at the new energy frontier of 13 TeV. The group is also leading the combination of tt cross section results of the CMS and ATLAS Collaborations at the LHC.

- **LHC Run-I Legacy: Most precise tt inclusive cross section measurements at 7 and 8 TeV in CMS.** In close collaboration with the DESY group and groups from IFCA (Spain), U. Oviedo (Spain) and IPHC (France), the YIG has published [1] a measurement of the inclusive tt production cross section at 7 TeV and 8 TeV using the full Run-I set of data. The tt production is identified via top-quark decays with an electron and a muon in the final

state. The cross sections are measured using statistical methods that allow constraining in situ the most relevant sources of systematic uncertainties. With this analysis strategy, the tt cross section is measured with a precision of 3.6% at 7 TeV and 3.7% at 8 TeV, challenging the state-of-the-art of theoretical precision and resulting in the most precise tt cross section results from the CMS Collaboration of the LHC Run-I.

- **First measurement of the inclusive tt cross section at 13 TeV using early 2015 data in CMS**. The measurement of the inclusive tt production cross section at CMS with the first data collected in June 2015 at 13 TeV (so-called CMS "Early Analysis") has been accepted by the journal [2].

- **Determination of the top-quark mass from the tt+1jet distribution at 8 TeV in CMS.** The group has performed the determination of the top-quark mass from the normalized differential cross section as a function of the invariant mass of the tt system and the highest-p_T additional jet (tt+1jet) in the dilepton channel, using 8 TeV data at CMS. This differential cross section is expected by some theorists to be particularly sensitive to the top-quark mass because the amount of gluon radiation depends on its value. The top-quark mass is extracted by comparing the measured tt +1jet differential cross section to NLO predictions. This way, the top-quark mass is determined in a well-defined theoretical scheme as used in perturbative QCD calculations (e.g pole mass), as opposed to the (most precise) direct measurements that rely heavily on less-well defined top-quark masses from MC simulations. The extracted top-quark mass is in agreement, within large uncertainties, with other top-quark pole mass results and with the more precise direct top-quark mass measurements. The analysis, performed together with a PhD student from the DESY group, has been released as a preliminary result by the CMS Collaboration [3].

- **Towards the first combination of tt differential cross sections from ATLAS and CMS.** Within the LHCtopWG, the YIG is leading the effort from the CMS side on the first combination of normalized tt differential cross section measurements from ATLAS and CMS using 8 TeV data. Both the observables to combine and the corresponding binning of the data were agreed on. The current focus of the work is on determining the proper mapping between the systematic uncertainties in the ATLAS and CMS measurements and their correlation among the different bins, as well as on investigating the proper statistical tools for the combination.

- **First differential tt production cross sections at 13 TeV in CMS.** The YIG has measured the normalized differential tt production cross section in the dilepton channel at CMS, using the full set of data at 13 TeV collected in 2015 (L = 2.2 fb^{-1}). The tt cross section is measured as a function of the kinematic properties of the top quarks, the tt system, and of the number of jets in the event. The measurements are confronted with modern SM MC generators. In addition, the top quark and tt observables are compared to several new QCD calculations that offer beyond-NLO accuracy. In general, the data are in agreement with the SM predictions for all distributions, within the uncertainty of the measurements. However:
  - The jet multiplicity in data is not properly described by any of the considered MC predictions for high multiplicity values.
  - A similar slope in the p_T(top) spectrum in data as observed in Run-I is also present at 13 TeV, and is better described by QCD calculations beyond NLO accuracy.

  The result has been published as a preliminary result [4] and will be included in a journal publication (in preparation [5]), and has been featured in the "DESY Highlights" brochure for 2016 (in preparation). The group is currently analyzing the full 2016 dataset (L = 36 fb^{-1}), also extending on the type of observables to measure, cross section definitions (fiducial and extrapolated to the full phase space), and kinematic range.

Measurements of associated production of top quark pairs and jets (tt+jets, tt+bb) at CMS

- **First measurement of tt+jets and tt+bb production at 8 TeV in CMS.** The YIG, in close collaboration with the DESY group, has published the measurement of the cross section for tt production with additional jet activity (tt+jets), including b quark jets (tt+b, tt+bb), in the dilepton channel at 8 TeV [6]. The work on the measurements of these distributions at 13 TeV is starting. Close collaboration with theorists from the DESY group (S. Moch) has been established to improve the tt+bb predictions at NLO with parton-level MC generators. In addition, the YIG is also involved in the effort of homogenizing the b jet definition among CMS and ATLAS that will allow for better comparison of the experimental data.

Associated tt production with a Higgs boson (tt+H(→bb)) in CMS

The YIG is also playing a leading role in the Higgs Physics Analysis group at CMS.

- **First search for tt+H(→bb) production at 13 TeV in CMS.** Together with the KIT group, and in collaboration with ~15 international institutes, the YIG is playing a key role in the search for the associated production of a Higgs boson with a top quark pair (tt+H), where the Higgs boson decays into a bb pair (H→bb), at 13 TeV. In order to increase the sensitivity of the search, selected events are split into several categories with different expected signal and background rates. In each category, signal and background events are separated pioneering a multivariate approach that combines a matrix element method with multivariate analysis techniques (e.g, boosted decision trees). The YIG is leading the search in final state with two leptons, building up from the tt cross section analysis at 13 TeV. First searches using the full dataset from 2015 (L = 2.7 fb^{-1}) [7] and a small dataset from 2016 (L = 12.9 fb^{-1}) [8] have been published as preliminary publications, and indicate that more data are needed to possibly claim an observation of the tt+H(→bb) process. The result on 2016 data is featured in the "DESY Highlights 2016" brochure (in preparation).
  The current focus of the work is on analyzing the full 2016 dataset.

Physics objects performance and MC validation

- Within the CMS Top Quark Physics Analysis Group, the YIG is providing crucial contributions to the validation and tuning of the tt simulation samples produced with improved MC generators for Run-II. Some of the distributions measured in [9] have been used by the CMS Collaboration to improve the modelling of the tt MC simulation that is used in top-quark measurements of 2016 data.

- The YIG is actively involved in the determination of the electron and muon identification and isolation efficiencies, dilepton trigger efficiencies, and the corresponding data-to-MC correction factors. These ingredients are crucial input for the correct measurement of the tt and tt+H processes pursued in the project, and have been incorporated successfully to the publications by the group and are also used elsewhere in the CMS Collaboration.

- A member of the YIG is coordinating and developing, within the Top Quark Physics Analysis Group, the trigger strategy to be used in top-quark-related measurements of 2017 data, as well as the corresponding performance studies. This work is essential to ensure the proper trigger rates that will allow performing top-quark measurements at CMS with the data-taking conditions for this run period.

Investigation and participation in novel design options for the CMS tracker upgrade

Within the DESY CMS Tracker Upgrade group, the YIG is leading the development of a novel automated assembly system of detector modules for the upgraded CMS tracker for the HL-LHC, planned to start in 2026. DESY, in collaboration with other institutions in Germany and abroad, is responsible for building one tracker end-cap. The upgraded CMS tracker will consist of detector modules providing particle momentum measurements at the hit-level, which is crucial for the trigger performance in the challenging data-taking conditions of the HL-LHC. The momentum measurement is performed by correlating hits in two closely-spaced silicon sensors within the module. As a result, the relative alignment of the two sensors must not be worse than 40 microns. As corrections for sensor misalignments within a module are not possible after module production or in the track reconstruction algorithms, the relative alignment constraints must be met at the module assembly stage. The YIG is developing an automated module assembly system, together with an assembly procedure, that meets the precision constraints, while offering improvements in cost, speed, and required manual labour associated with the module production with respect to manual approaches.

Development of an automated module assembly of detector modules
An assembly setup consisting of a motion stage, sensor handling vacuum tool, and high-resolution camera has been designed and commissioned by the YIG to provide the desired automation. In addition, a software application has been developed to integrate these tools. The software obtains images of module components and processes them with a dedicated pattern-recognition algorithm, also designed by the group. The algorithm precisely deduces the location of module components and assembles them to the required precision via control of the motion and handling systems. Core aspects in the commissioning of the automated assembly have been addressed in the context of a summer student project supervised by a member of the YIG.

In order to speed up significantly the module production process, the automated assembly must reduce the 24-hour glue curing time between assembly steps needed in manual approaches. During that time, the assembly platform would remain inoperable while holding the components tightly in place. The YIG is developing a gluing procedure where extremely small amounts of a fast-curing epoxy glue is used in addition to the low-viscosity, radiation-hard glue needed for the large-area glue joints of the assembled module. Instead of the assembly platform, the epoxy provides fixation and thus makes the automated assembly readily available for the next module. The feasibility and fundamental precision capabilities of the setup have been presented at the CMS Tracker Upgrade community (Dec 2016).

- **Design and test of gluing procedures for automatic module assembly.** The YIG has investigated a range of possible glues for both large-area and fast gluing application, as well as different geometrical layout options for bonding. The study focused on the following properties of the adhesives and layouts: curing time; glue layer thickness, profile and viscosity; required amount of fast glue; interaction/contamination of fast and large-area glues. Practicable candidates have been identified, resulting in a procedure that requires only 15 minutes of curing time between assembly steps. This yields the potential for dramatic improvements in module production speed. The conclusions have been presented to the CMS Tracker Upgrade Collaboration at CERN.

- **Development and commissioning of an automated plasma cleaner system.** The assembled modules will be integrated into the tracker via mounting on semi-circular, carbon fibre structures known as „Dees“. The usage of plasma cleaning of the Dees has been investigated in order to improve both adhesion between the module and the Dee and handling in this integration step. The YIG has contributed to the design and commissioning of a motion stage and associated software permitting precise control of the commercial plasma cleaner. In particular, the necessary software has been

developed and implemented by the group to control the motion stage on which the cleaner head is mounted, and first tests of the integrated cleaner-stage setup have been performed. The latter has been carried out in the context of a summer student project supervised by a member of the YIG.

Further responsibilities of the group members (alphabetically ordered)**:**

Dr. M. Aldaya:
- Co-coordinator of the CMS Top Cross Sections subgroup (L3) (started: 01.09.2015)
- CMS coordinator of the combination of tt differential cross section results of the CMS and ATLAS Collaborations within the Top LHC Working Group
- Member of the CMS Analysis Review Committee (editorial board)
- Reviewer for Eur. Phys. Journal C (since July 2014)
- Chair of the *Top Quark V (Wirkungsquerschnitte)* session of the DPG-Frühjahrstagung Hamburg (Germany), 29 Feb – 4 Mar 2016
- Chair of the *Differential Cross Sections* session at TOP2016: 9th International Workshop on Top Quark Physics, Olomouc (Czech Republic), 18 – 23 Sep 2016
- Chair of the *Top Quark* and *Top and Higgs* sessions of the 10th Annual Meeting of the Helmholtz Alliance „Physics at the Terascale“, DESY Hamburg (Germany), 21 – 23 Nov 2016
- Co-organizer of the CMS workshop: Towards ultimate precision on top cross sections with the 2016 dataset, CERN Geneva (Switzerland), 29 April 2016
- Co-organizer of the CMS workshop: Top @ 100 fb^{-1}, CERN Geneva (Switzerland), 8 – 9 Nov 2016

Dr. C. Diez Pardos:
- Co-coordinator of the CMS Top Mass subgroup (L3) (started: 01.09.2016)
- Contact person between the Top Quark Physics Analysis and Muon Performance Groups in CMS (ended: 01.04.2016)
- Contact person between the Top Quark Physics Analyses and the Trigger Studies groups in CMS (started: 01.04.2016)
- Co-coordinator of the CMS Top-Higgs Forum (started: 01.09.2016)
- Member of the CMS Analysis Review Committee (editorial board)
- Reviewer for Eur. Phys. Journal C (since November 2016)
- Supervisor of summer student at the DESY Summer Student Programme 2016
- Chair of the *Top and Higgs* session at TOP2016: 9th International Workshop on Top Quark Physics, Olomouc (Czech Republic), 18 – 23 Sep 2016
- Chair of the *Top Quark* session of the CMS FSP Workshop, DESY Hamburg (Germany), 5 – 7 Oct 2016

Dr. J. Hauk:
- Coordinator of the working meetings of the CMS ttH(→bb) Working Group (ended: 13.04.2016, due to parental leave)

Dr. J. Keaveney:
- Coordinator of the CMS Top Cross Sections subgroup (L3) (ended: 10.11.2016)
- Member of the CMS Analysis Review Committee (editorial board)
- Supervisor of summer student at the DESY Summer Student Programme 2016
- Co-organizer of the CMS workshop: Towards ultimate precision on top cross sections with the 2016 dataset, CERN Geneva (Switzerland), 29 April 2016
- Co-organizer of the CMS workshop: Top @ 100 fb^{-1}, CERN Geneva (Switzerland), 8 – 9 Nov 2016

M. Savitskyi:
- Contact person between the Top Quark Physics Analysis and Monte Carlo Generator Groups

in CMS

5) Financial Plan / Time Schedule

Can you comply with the financial plan and time schedule or do you see a need for adjustment?

The expenses for personnel, investments and travel, including the CMS operation fees, correspond to financial plan of the proposal. Investments include: Loctite UV glue, linear motion stage and controller for plasma cleaning setup. There is no need to adjust the financial plan or the time schedule.

6) Status

Do you hold a joint Junior Professorship or a W2/W3 Professorship? Do you aim for such a position? What is the status of your negotiations in this respect?

The group leader does not hold a junior professorship or a W2/W3 professorship. Negotiations aiming at such a position have not started yet.

7) Teaching Activities of the Group Leader

During the report period, the group leader has had the following teaching activity:

- Shared lecture at the summer semester master programme: “Teilchenphysik II – W, Z, Top am Collider” at the University of Karlsruhe. 15 lecturing hours.

8) Publications of the Group

Public presentations by the group members:

- J. Hauk, *The Top Quark and the Higgs boson: Vital Actors at LHC*, invited talk at DPG-Frühjahrstagung Hamburg (Germany), 29 Feb – 4 Mar 2016
- M. Savitskyi, *Measurement of the differential cross section for top-quark pair production in the dilepton channel at 13 TeV with the CMS detector*, parallel talk at DPG-Frühjahrstagung Hamburg (Germany), 29 Feb – 4 Mar 2016
- J. Hauk, *Results and prospects for ttH at CMS*, plenary talk at 51st Rencontres de Moriond EW 2016, La Thuile (Italy), 12 – 19 Mar 2016
- J. Keaveney, M. Aldaya, *Introduction and top cross section prospects with 30 fb^{-1}*, opening talk at the CMS workshop: Towards ultimate precision on top cross sections with the 2016 dataset, CERN Geneva (Switzerland), 29 April 2016
- C. Diez Pardos, *Prospects for modeling of trigger, lepton ID and isolation efficiencies*, invited talk at the CMS workshop: Towards ultimate precision on top cross sections with the 2016 dataset, CERN Geneva (Switzerland), 29 April 2016
- M. Savitskyi, *Towards ultimate precision in dilepton channel (differential)*, invited talk at the CMS workshop: Towards ultimate precision on top cross sections with the 2016 dataset, CERN Geneva (Switzerland), 29 April 2016
- M. Aldaya, *Recent results on top quark physics,* invited plenary talk at the 28th Rencontres de Blois on Particle Physics and Cosmology, Blois (France), 29 May – 3 June 2016
- J. Keaveney, *Top pair cross section measurements (incl./diff.) and event modelling with the CMS detector*, parallel talk at ICHEP 2016: 38th International Conference on High Energy Physics, Chicago (USA), 3 – 10 Aug 2016; proceedings: PoS(ICHEP2016)653
- M. Savitskyi, *Measurement of the differential cross section for top-quark-pair production in the dilepton channel at 13 TeV with the CMS detector*, poster at TOP2016: 9th International Workshop on Top Quark Physics, Olomouc (Czech Republic), 18 – 23 Sep 2016; proceedings: arXiv:1611.09657 [hep-ex]

- C. Diez Pardos, *tt cross section measurements in CMS*, plenary talk at TOP2016: 9th International Workshop on Top Quark Physics, Olomouc (Czech Republic), 18 – 23 Sep 2016; proceedings: arXiv:1611.06524 [hep-ex]
- M. Aldaya, et al., *Top quark pair cross section measurements @ 100 fb^{-1}: introduction and context*, talk at the CMS workshop: Top @ 100 fb^{-1}, CERN Geneva (Switzerland), 8 – 9 Nov 2016
- J. Keaveney, *New σ_{tt} analyses,* talk at the CMS workshop: Top @ 100 fb^{-1}, CERN Geneva (Switzerland), 8 – 9 Nov 2016
- C. Diez Pardos et al., *Top mass with 100 fb^{-1},* talk at the CMS workshop: Top @ 100 fb^{-1}, CERN Geneva (Switzerland), 8 – 9 Nov 2016
- K. el Morabit et al., *Recent CMS results on the search for ttH production*, parallel talk at 10th Annual Meeting of the Helmholtz Alliance „Physics at the Terascale“, DESY Hamburg (Germany), 21 – 23 Nov 2016
- M. Aldaya et al., *Top Quark Physics at the LHC*, poster at MUTAG2016: 2nd Annual Symposium of the Helmholtz Programme Matter and the Universe, Helmholtz Institute Mainz (Germany), 12 – 13 Dec 2016

Relevant publications, approved public results, and publications in preparation (preliminary public results by the group that are superseded by the corresponding journal publication are not included)

[1] CMS Collaboration, *Measurement of the tt production cross section in the eμ channel in pp collisions at sqrt(s) = 7 and 8 TeV,* J. High Energy Phys. 08 (2016) 029, arXiv:1603.02303 [hep-ex]
[2] CMS Collaboration, *Measurement of the top quark pair production cross section in proton-proton collisions at sqrt(s) = 13 TeV*, Phys. Rev. Lett. 116 (2016) 052002, arXiv:1510.05302 [hep-ex]
[3] CMS Collaboration, *Determination of the normalized invariant mass distribution of tt+1jet and extraction of the top quark mass*, CMS Physics Analysis Summary CMS-PAS TOP-13-006 (2016)
[4] CMS Collaboration, *Measurement of the differential cross section for ttbar production in the dilepton final state at 13 TeV*, CMS Physics Analysis Summary CMS-PAS TOP-16-011 (2016)
[5] CMS Collaboration, *Measurement of particle level differential tt cross sections in the dilepton channel at sqrt(s) = 13 TeV*, CMS Physics Analysis Summary CMS-PAS TOP-16-007 (2016); journal publication in preparation
[6] CMS Collaboration, *Measurement of ttbar production with additional jet activity, including b quark jets, in the dilepton decay channel using pp collisions at sqrt(s) = 8 TeV,* Eur. Phys. J. C 76 (2016) 379, arXiv:1510.03072 [hep-ex]
[7] CMS Collaboration, *Search for ttH production in the H->bb decay channel with sqrt(s) = 13 TeV pp collisions at the CMS experiment*, CMS Physics Analysis Summary CMS-PAS HIG-16-004 (2016)
[8] CMS Collaboration, *Search for ttH production in the H->bb decay channel with 2016 pp collision data at sqrt(s) = 13 TeV*, CMS Physics Analysis Summary CMS-PAS HIG-16-038 (2016); journal publication in preparation

Other publications with important contributions from the YIG

- CMS Collaboration, *Measurement if the tt production cross section using events in the e□ final state in pp collisions at sqrt(s) = 13 TeV,* submitted to Eur. Phys. J. C, arXiv:1611.04040 [hep-ex]
- CMS Collaboration, *Search for standard model production of four top quarks in proton-*

proton collisions at sqrt(s) = 13 TeV, CMS Physics Analysis Summary CMS-PAS TOP-16-016 (2016); journal publication in preparation

- CMS Collaboration, *Measurement of double differential cross sections for top quark pair production in pp collisions at 8 TeV*, CMS Physics Analysis Summary CMS-PAS TOP-14-013 (2016); journal publication in preparation
- CMS Collaboration, *First measurement of the top quark pair production cross section in proton-proton collisions at 5.02 TeV*, CMS Physics Analysis Summary CMS-PAS TOP-16-015 (2016); journal publication in preparation

9) External Funding

10) Patent Applications
No. of pending/granted patents

11) Awards received by Group Members / Professorship Appointments offered to Group Leader