

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):	01/2015-12/2015

1) Group Structure

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

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

Post-doctoral researchers:

- Dr. Carmen Diez Pardos (started 01.04.2014)
- Dr. Johannes Hauk (started 01.12.2015)

PhD students:

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

Comments:

- Dr. Hauk is employed by the YIG since 01.12.2015 for a total period of 1 year to work on the tt+H analysis and the tracker upgrade projects. However, he started his work within the YIG already since 01.08.2015, as soon as it was agreed that he would join the group.

- The funding for Mr. El Morabit is provided by the Partner University KIT, as agreed originally in the proposal.

- Dr. James Keaveney will be employed by the group starting in January 2016 to work on the tracker upgrade project.

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.

Since May 2015, the YIG leader is an associated scientist in the renewed Karlsruhe Research Training Group GRK 1694: *Elementarteilchenphysik bei höchster Energie und höchster Präzision* (Graduiertenkolleg).

Since July 2015, the YIG leader is also:

- The 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.
- The coordinator of the CMS Top Quark Physics group at DESY (composed, as of December 2015, of 4 staff scientists, 7 post-doctoral researchers, and 7 PhD students), initiating and coordinating the analyses carried out by the group, and guiding the work of the PhD students and post-doctoral researchers.
- The leader of the DESY CMS-F1 subgroup, which comprises the Young Investigator Group and additional personnel (as of December 2015: 1 staff scientist, 1 post-doctoral researcher, 3 PhD students).

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, in general, 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 ($t\bar{t}$) production at the LHC, the measurement of $t\bar{t}$ production in association with a Higgs boson ($t\bar{t}+H$) 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 ($t\bar{t}$) production at CMS and combination of results from the CMS and ATLAS Collaborations

The group continues playing a key role in the Top Quark Physics Analysis Group of the CMS experiment and works closely together with the DESY CMS Top Quark Physics group. In addition, the group is leading the combination of $t\bar{t}$ cross sections results of the CMS and ATLAS Collaborations at the LHC.

- The group has published the measurement of the $t\bar{t}$ differential production cross sections at $\sqrt{s} = 8$ TeV using the full Run-I data set [1]. The measurement is performed in the final states with two leptons (electron-electron, muon-muon, electron-muon, the so-called dilepton channels) as well as in $t\bar{t}$ final states with one lepton ($l+jets$ channel). The cross sections are determined as a function of the kinematic properties of leptons, jets, top (antitop) quarks, and the $t\bar{t}$ system. The results are compared to different Standard Model (SM) predictions and no deviations from the SM are observed. However, the top quark transverse momentum ($p_T(top)$) has been found to be lower than the predictions up to Next-to-Leading-Order (NLO) accuracy in QCD perturbation theory, but better described by a prediction beyond NLO. The tail of the invariant mass of the $t\bar{t}$ system ($m(t\bar{t})$) is also not well described by the predictions. The measurements have been performed in collaboration with the DESY and the University of Hamburg groups, and constitute the final word of the LHC Run-I on $t\bar{t}$ differential cross section results in the dilepton and $l+jets$ channels at CMS.

- In close collaboration with the DESY group and groups from IFCA (Spain), University of Oviedo (Spain) and IPHC (France), the YIG is working on the „Run-I legacy“ measurement of the inclusive $t\bar{t}$ production cross section at $\sqrt{s} = 7$ TeV and 8 TeV using the full Run-I set of data. The $t\bar{t}$ production is identified via top quark decays with an electron and a muon in the final state. The cross sections are measured by performing a maximum likelihood fit in different event categories and constraining the most relevant systematic uncertainties. This analysis strategy leads to much improved precision with respect to the current existing CMS measurements. In addition, the $t\bar{t}$ cross sections are used to extract the top quark pole mass, and to set limits on stop quark production. The analysis has been published as a preliminary result [2], and the journal publication is in preparation. These results are expected to be the final word of the LHC Run-I on $t\bar{t}$ cross section measurements in dilepton channels at CMS.
- Within the CERN LHC Top Working Group, the YIG is leading the effort from the CMS side in determining the compatibility of the $t\bar{t}$ differential cross section results from ATLAS and CMS, which is a necessary step towards possible combinations. For the first time ever, qualitative comparison studies of the $t\bar{t}$ differential cross sections measurements from ATLAS and CMS have been performed. The studies based on 8 TeV data show consistency between the two experiments. Furthermore, the latest ATLAS measurements confirm the CMS results on the $p_T(\text{top})$ and $m(t\bar{t})$ spectra [1]. In addition, the ATLAS and CMS data have been confronted with different Monte Carlo (MC) predictions and the recently released full Next-to-Next-to-Leading-Order (NNLO) accuracy calculation for different kinematic distributions of the top quarks and $t\bar{t}$ system. An outcome of this comparison is that the top quark p_T spectrum in ATLAS and CMS is better described by the NNLO prediction, although all predictions fail to describe well the tail of the distribution. This has triggered further studies and discussions within the theory community that are currently ongoing.
- The group is also working on the first determination of the top quark pole mass from the $t\bar{t}$ differential cross section as a function of the invariant mass of the $t\bar{t}$ system and one additional jet ($t\bar{t}+1\text{jet}$) using 8 TeV data at CMS [3]. The top quark pole mass is extracted by comparing the measured $t\bar{t}+1\text{jet}$ differential cross section to different NLO predictions. This approach, as in the analysis described in [2], allows determining the top quark mass in a well defined renormalization scheme, in contrast to the most commonly used techniques to determine the top quark mass from the invariant mass of the top quark decay products. The analysis, which is performed together with a PhD student from the DESY group, is under review by the CMS Collaboration and the preliminary publication is in preparation.

Measurements of associated production of top quark pairs and jets ($t\bar{t}+1\text{jets}$, $t\bar{t}+bb$) at CMS

- The YIG, in close collaboration with the DESY group, has published the measurement of $t\bar{t}$ production with additional jet activity ($t\bar{t}+1\text{jets}$), including b quark jets ($t\bar{t}+bb$), in the dilepton channel at $\sqrt{s} = 8$ TeV [4]. The measurement is performed differentially as a function of the number of jets in the event and of the kinematic properties of the additional jets. For the first time at the LHC, the kinematic properties of additional high p_T b jets produced in association with $t\bar{t}$ events are measured differentially in $t\bar{t}+b$ and $t\bar{t}+bb$ production. This analysis is crucial not only because it affords rigorous tests of perturbative QCD, but also because it supplies essential information for the measurement of Higgs boson properties and for searches for phenomena beyond the SM, as it is one of the main background contributions to these processes. Good experimental knowledge of these processes pave the way to the observation of the Higgs boson in association with a top quark pair ($t\bar{t}+H$) and to the measurement its couplings to top and b quarks. Members of the group also worked in close collaboration with theory colleagues (M.V. Garzelli) to provide an NLO $t\bar{t}+bb$ calculation for comparison with data. Moreover, the YIG is also involved in ongoing discussions between CMS and ATLAS towards a common definition of b jets that would

allow for better comparison of the experimental data.

First tt and associated tt production with a Higgs boson (tt+H(\rightarrow bb)) measurements at CMS for the LHC Run-II

- The YIG took over the responsibility within the CMS Top Quark Physics Group to contribute to the validation of tt simulation samples produced with improved MC generators for Run-II at $\sqrt{s} = 13$ TeV. Based on this validation, the choice of the baseline tt simulation to be used with CMS data collected in 2015 was made.
- The group, together with the DESY group and in collaboration with U. Oviedo (Spain), U. Ghent (Brussels), IFCA (Spain), U. Riverside (US), and IPHC (France), has published the first measurement of the inclusive tt production cross section at CMS with the first data collected in June 2015 at $\sqrt{s} = 13$ TeV (so-called CMS „Early Analysis“). The measurement is performed in the electron-muon final state, which is especially suited due to the low contamination from background processes. A robust analysis technique based on counting of tt events is chosen over more involved methods to calculate the cross section at this early stage of the understanding of the CMS detector at the new energy regime. The result was published first as a preliminary result and then as a journal publication [5]. This result is featured in the „DESY Highlights 2015“ brochure (in preparation).
- The YIG has measured the differential tt production cross section at CMS using early data at 13 TeV. The analysis is performed in the dilepton channel and constitutes the first tt differential cross section measurement of the LHC at this new energy [6]. 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 several SM MC predictions and found to be in good agreement. The current precision is not enough to confirm the trends observed in the differential distributions in Run-I [1]. Therefore, an update of the analysis using the complete set of data collected in 2015 is planned. The result has been published as a preliminary result.
- In close collaboration with the DESY and KIT groups, and in collaboration with ~15 international institutes (among them: Ohio State U. (US), U. Virginia (US), U. Notre Dame (US) and ETH (Zurich)), the YIG is setting up the analysis framework to perform the search for the associated production of a Higgs boson with a top quark pair (tt+H) at 13 TeV, using the full dataset of 2015. The tt production is identified via top quark decays with two leptons in the final state, and the Higgs boson decays into a b quark pair (H \rightarrow bb). The analysis builds up from the tt cross section analysis at 13 TeV and makes use of multivariate analysis techniques to increase the sensitivity of the search. In addition, first studies of tt+H production at high p_T (so-called boosted regime) have been performed in the context of a summer student project.
- In the context of the tt inclusive and differential measurements, and the tt+H analysis at 13 TeV, the group has been also involved in the determination of the electron and muon identification and isolation efficiencies, the 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, and have been incorporated successfully to the publications [5,6].

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

- In close collaboration with the DESY Tracker Upgrade Group, the YIG is working on first studies for the characterization of high performance materials that are foreseen to be used in the support structures of the silicon modules of the upgraded CMS tracker for the High-Luminosity LHC. In particular, the group is investigating phase-change thermal interface

materials as possible glue types for the different components of the support structure for the silicon modules, as well as feasible techniques for the application of the glue to the components of the silicon modules.

- The construction of the CMS upgrade tracker modules requires an automated assembly system that can arrange sensor components to a high precision. The YIG has taken over the responsibility of contributing to the design of an experimental setup to meet this need. This also implies the design of a dedicated pattern recognition and hardware control software package.
- The upgraded CMS tracker is foreseen to be instrumented with detector modules capable of measuring track momentum locally and sending high-momentum measurements to a real-time processor embedded in the level-1 trigger. Each module consists of two closely spaced silicon sensor layers. Curved trajectories of charged particles above a certain p_T threshold of about 2 GeV can be identified by spacially coincident clusters in both layers, from which short track segments (stubs) are reconstructed. Specific chips were developed to perform the correlation logic on-board and send the stub information to the level-1 trigger and to buffer the full signal information for triggered readout, the CMS Binary Chip (CBC). The group is involved in the editorial stages of the publication of a test beam analysis of a functional CBC prototype.

Responsibilities of the group members:

M. Aldaya:

- Coordinator of the DESY CMS Top Quark Physics Group
- CMS coordinator of the combination of tt inclusive cross section results of the CMS and ATLAS Collaborations within the Top LHC Working Group (ended: 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
- Co-coordinator of the CERN CMS Top Cross Sections Group (started: 01.09.2015)
- Convenor of the CMS FSP Workshop, KIT Karlsruhe (Germany), 7 – 9 Oct 2015
- Convenor of the Top Quark Working Group of the 9th Annual Meeting of the Helmholtz Alliance „Physics at the Terascale“, DESY Hamburg (Germany), 17 – 18 Nov 2015

C. Diez Pardos:

- Contact person between the Top Quark Physics Analysis and Muon Performance Groups in CMS
- Coordinator of the working meetings of the DESY CMS Top Quark Physics Group
- Supervisor of summer student at the DESY Summer Student Programme 2015
- Coordinator of the student report sessions at the Maria Laach 47. Herbstschule fuer Hochenergiephysik, 8 - 18 Sep 2015

J. Hauk:

- Co-coordinator of the working meetings of the CMS ttH(→bb) Group (started: 01.09.2015)

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 and travel, including the CMS operation fees, correspond to financial plan of the proposal. 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:

- Lecturer on “Experimental Top Quark Physics” at the Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology (KSETA). 6 lecturing hours.

8) Publications of the Group

Public presentations by the group members:

- M. Aldaya, F. Spano, *ATLAS+CMS 8 TeV $t\bar{t}$ cross section combination and status and plans for differential distributions*, plenary talk at Open Meeting of the TOP LHC Working Group, CERN Geneva (Switzerland), 12 – 13 Jan 2015
- C. Diez Pardos, *Measurements of Top Quark Pair Production with the CMS Experiment*, invited talk at DPG-Frühjahrstagung Wuppertal (Germany), 9 - 13 Mar 2015
- M. Savitskyi, *First studies towards top-quark pair cross section measurement in the dilepton channel at 13 TeV with the CMS detector*, parallel talk at DPG-Frühjahrstagung Wuppertal (Germany), 9 - 13 Mar 2015
- C. Diez Pardos, *Status of CMS at DESY*, Report to the 79th Physics Research Committee, Hamburg (Germany), 11 May 2015
- M. Savitskyi, *First studies towards top-quark pair differential cross section measurement in the dilepton channel at $\sqrt{s} = 13$ TeV with the CMS detector*, “new talents” talk at the International school of subnuclear physics 2015: 53rd course: the future of our physics including new frontier, Erice (Italy), 24 Jun – 3 Jul 2015
- M. Aldaya, *Measuring the differential cross section for top quark pair production at 8 TeV*, poster at European Physical Society Conference on High Energy Physics 2015, Vienna (Austria), 22 – 29 Jul 2015
- C. Diez Pardos, *Measurements of $t\bar{t} + X$ with the ATLAS and CMS Experiments*, parallel talk at LHCP2015: The Third Annual Large Hadron Collider Physics Conference, St. Petersburg (Russia) 31 Aug - 5 Sep 2015, Proceedings CMS CR-2015/356
- M. Savitskyi, *First measurement of the differential cross section for $t\bar{t}$ production in the dilepton final state at $\sqrt{s} = 13$ TeV*, parallel talk at CMS FSP Workshop, KIT Karlsruhe (Germany), 7-9 Oct 2015
- M. Aldaya, *Recent top quark physics results from CMS*, invited plenary talk at CMS FSP Workshop, KIT Karlsruhe (Germany), 7-9 Oct 2015
- C. Diez Pardos, *13 TeV Forum: First Results from LHC Run-II*, plenary talk at DESY Physics Seminar, Hamburg and Zeuthen (Germany), 3-4 Nov 2015
- M. Savitskyi, *Differential cross section for $t\bar{t}$ production at 8 and 13 TeV*, parallel talk at 9th Annual Meeting of the Helmholtz Alliance „Physics at the Terascale“, DESY Hamburg (Germany), 17 – 18 Nov 2015
- C. Diez Pardos, *Top quark pair inclusive cross section in the $em\mu$ channel at 7, 8, and*

13 TeV with the CMS experiment, parallel talk at 9th Annual Meeting of the Helmholtz Alliance „Physics at the Terascale“, DESY Hamburg (Germany), 17 – 18 Nov 2015

- J. Hauk, *Measurement of tt production with additional jet activity, including b quark jets, in the dilepton decay channel using pp collisions at sqrt(s) = 8 TeV*, parallel talk at 9th Annual Meeting of the Helmholtz Alliance „Physics at the Terascale“, DESY Hamburg (Germany), 17 – 18 Nov 2015
- M. Aldaya, F. Spano, *ATLAS and CMS tt differential cross section measurements at sqrt(s) = 8 TeV*, plenary talk at Open Meeting of the TOP LHC Working Group, CERN Geneva (Switzerland), 17 – 18 Nov 2015
- C. Diez Pardos, *ATLAS and CMS inclusive top quark pair cross section measurements*, plenary talk at Open Meeting of the TOP LHC Working Group, CERN Geneva (Switzerland), 17 – 18 Nov 2015

Relevant publications, approved public results, and publications in preparation:

- [1] CMS Collaboration, *Measurement of the differential top quark pair production cross section in pp collisions at sqrt(s) = 8 TeV*, arXiv:1505.04480 [hep-ex], Eur. Phys. J. C 75 (2015) 542, (corr. authors: M. Aldaya, C. Diez Pardos, editor: M. Aldaya)
- [2] CMS Collaboration, *Measurement of the tt production cross section in the emu channel in pp collisions at sqrt(s) = 7 and 8 TeV*, CMS Physics Analysis Summary CMS-PAS TOP-13-004 (2015), journal publication in preparation (corr. author and editor: C. Diez Pardos)
- [3] CMS Collaboration, *Determination of the normalized invariant mass distribution of tt+1jet and extraction of the top quark mass*, preliminary result CMS-PAS TOP-13-006 in preparation (corr. author and editor: C. Diez Pardos)
- [4] 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*, arXiv:1510.03072 [hep-ex], submitted to EPJC (corr. authors: C. Diez Pardos, M. Aldaya, J. Hauk, editor: C. Diez Pardos)
- [5] CMS Collaboration, *Measurement of the top quark pair production cross section in proton-proton collisions at sqrt(s) = 13 TeV*, CMS Physics Analysis Summary CMS-PAS TOP-15-003 (2015) and journal publication arXiv:1510.05302 [hep-ex], submitted to Phys. Rev. Lett. (corr. authors: M. Savitskyi, M. Aldaya)
- [6] CMS Collaboration, *First measurement of the differential cross section for ttbar production in the dilepton final state at 13 TeV*, CMS Physics Analysis Summary CMS-PAS TOP-15-010 (2015) (corr. authors: M. Savitskyi, M. Aldaya, editor: M. Aldaya)

9) External Funding

10) Patent Applications

No. of pending/granted patents

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

The following awards have been received by members of the group:

- M. Savitskyi: Diploma for “Best experimental new talent presentation” and B. Rossi Diploma for excellent performance, both at the International school of subnuclear physics 2015, Erice (Italy), 24 Jun – 3 Jul 2015