

Annual Report

<b>Funding Programme:</b>	Helmholtz Young Investigators Groups
<b>Project ID No.:</b>	VH-NG-1004
<b>Project Title:</b>	Ultimate precision measurements and searches for new physics using top quarks at the CMS experiment at the LHC
<b>Group Leader:</b>	Dr. Maria Aldaya Martin
<b>Helmholtz Centre:</b>	DESY
<b>Participating University:</b>	Karlsruhe Institute of Technology (KIT, University Sector), Hamburg
<b>Report Period (=Calendar Year):</b>	01/2018-03/2019

**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 (01.04.2014 – 31.12.2018)
- Dr. Johannes Hauk (01.12.2015 – 30.06.2017, on parental leave from 13.04.2016 to 12.11.2016)
- Dr. James Keaveney (15.01.2016 – 28.02.2019)
- 3 DESY Fellows have joined the YIG (2 since January 2016, 1 since August 2017) to work on the tt+H analysis for 30% of their time

PhD students:

- Mr. Mykola Savitskyi (01.09.2014 – 31.07.2018, University of Hamburg)
- Mr. Andrej Saibel (started 15.02.2017, University of Hamburg)

Additional information:

Dr. Diez Pardos accepted a permanent scientist position at the physics department of the University of Siegen (Germany) and is now member of the ATLAS Collaboration (since 01.01.2019)

Dr. Keaveney accepted a faculty position at the physics department of the University of Cape Town (South Africa) and joined the ATLAS Collaboration (since 01.03.2019)

Dr. Savitskyi accepted the offer of a post-doctoral position within the DESY Fellowship Programme (since 01.09.2018)

Mr. Saibel was employed by the U. Hamburg ("II. Institut für Theoretische Physik") during 01.02.2018 - 31.12.2018 to work with Prof. Dr. Sven-Olaf Moch on differential cross section calculations for tt+H, in addition to his experimental analysis of CMS data.

**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. Additional close cooperation with the theory department of the U. Hamburg (“II. Institut für Theoretische Physik”) has been established through a shared PhD student (A. Saibel).

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

Dr. M. Aldaya

- Since 2015 Leader of the DESY CMS subgroup 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 YIG is embedded in CMS-F1.
- Since 2014 Coordinator of the DESY-CMS Top Quark Physics Group at DESY Hamburg (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

- 2014 – 12.2018 Coordinator of the working meetings of the DESY-CMS Top Quark Physics Group at DESY Hamburg.

Dr. J. Keaveney

- 2016 – 02.2019 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 ( $t\bar{t}$ ) production at CMS and 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 has progressed 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 is well established as key player in the Top Quark Physics Analysis Group of the CMS experiment. The YIG continues to contribute strongly to precision  $t\bar{t}$  cross section measurements at the new energy frontier of 13 TeV. The group is also leading the combination of  $t\bar{t}$  cross section results of the CMS and ATLAS Collaborations at the LHC.

- **Towards the first combination of  $t\bar{t}$  differential cross sections from ATLAS and CMS in LHC Run1.** Within the LHCtopWG, the YIG is leading the effort from the CMS side on the first combination of normalized  $t\bar{t}$  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 proper mapping between the systematic uncertainties in the ATLAS and CMS measurements has been determined. A number of statistical tools have been investigated and compared. A preliminary assessment of the correlation of the different sources of systematic uncertainties among the different bins of a given observable and across experiments has been performed. First preliminary results for the combination of the  $t\bar{t}$  differential cross section as a function of the transverse momentum of the top quark,  $p_T(\text{top})$ , invariant mass of the  $t\bar{t}$  system,  $m(t\bar{t})$ , and  $p_T$  of the  $t\bar{t}$  system,  $p_T(t\bar{t})$ , have been presented to ATLAS and CMS and show a significant improvement in the precision with respect to the individual results. A journal publication is in preparation.
- **First differential  $t\bar{t}$  production cross sections at 13 TeV in CMS.** The first measurement of normalized differential  $t\bar{t}$  production cross sections in final states with two leptons (dilepton channel) at CMS, using the full set of data at 13 TeV collected in 2015 ( $L = 2.2 \text{ fb}^{-1}$ ) has been published [1].
- **Differential  $t\bar{t}$  production cross sections at 13 TeV in CMS.** The YIG has published [2] absolute and normalized differential  $t\bar{t}$  production cross section in final states with two leptons at CMS, using the full set of data at 13 TeV collected in 2016 ( $L = 36 \text{ fb}^{-1}$ ). This work extends the scope of the previous result [1] in terms of the type of observables to measure and cross section definitions. The differential cross section are measured as functions of kinematic observables of the top quarks and their decay products (leptons, b-jets), the  $t\bar{t}$  system, as well as of the total number of jets in the event. The differential cross sections are defined both with particle-level objects in a fiducial phase space close to that of the detector acceptance, and with parton-level top quarks in the full phase space. A total of 98 different measurements have been performed. All results are compared with standard model predictions from Monte Carlo (MC) simulations with next-to-leading-order (NLO) accuracy in QCD at matrix-element level interfaced to parton-shower simulations. Most measured differential cross sections are well modelled by the predictions. However, significant disagreement is observed between data and NLO MC predictions is observed for a number of distributions:
  - the  $p_T$  of top quarks, leptons, b-jets, and  $t\bar{t}$ ,  $b\bar{b}$ , and  $l\bar{l}$  systems
  - the invariant mass of  $t\bar{t}$ ,  $b\bar{b}$ , and  $l\bar{l}$  systems
  - the jet multiplicity distribution for high multiplicities
  - the azimuthal angle between the two leptons

The parton-level results are also compared to the state-of-the-art calculations with beyond NLO precision in QCD. In particular, the NNLO (QCD) with NLO EW corrections is shown to improve the description of the  $p_T(\text{top})$  distribution, hinting that missing higher-order corrections are further needed in the theoretical calculations.

In addition, the absolute particle-level differential cross sections are used, for the first time ever, to constrain the top quark chromomagnetic dipole moment in an Effective Field Theory framework at NLO in QCD, while the normalized results are used to extract, for the first time at 13 TeV at the LHC,  $t\bar{t}$  and leptonic charge asymmetries.

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

- **First differential  $tt+bb$  production cross sections at 13 TeV in CMS.** The YIG is working on the measurement of the cross section for  $tt$  production with additional  $b$ -jets ( $tt+b$ ,  $tt+bb$ ), in the dilepton channel at 13 TeV using the full Run2 dataset ( $L \sim 150\text{fb}^{-1}$  of data collected within 2016-2018). The measurement is performed differentially as a function of the kinematic properties of additional high  $p_T$   $b$  jets produced in association with  $tt$  events, extending the scope of the YIG's previous result in terms of the type of observables to measure, cross section definitions (particle and parton level), and improved precision. An optimized use of machine-learning techniques is employed to improve the distinction of the  $b$ -jets not coming from  $tt$  events. In parallel, work with theorists from the DESY group (S. Moch, M.V. Garzelli) is ongoing to improve the  $tt+bb$  predictions at NLO with parton-level MC generators.

### Associated $tt$ production with a Higgs boson ( $tt+H(\rightarrow bb)$ ) in CMS

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

- **Search for  $tt+H(\rightarrow bb)$  production at 13 TeV in CMS.** Together with the KIT group, and in collaboration with  $\sim 15$  international institutes, the YIG has published [3] 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 ( $H\rightarrow bb$ ), analyzing the full set of data at 13 TeV collected in 2016. The YIG has led the search in final state with two leptons, building up from the previous work published in 2016 based on a partial dataset at 13 TeV.

In order to increase the sensitivity of the search, events are split into several categories according to number of leptons, jets, and  $b$ -jets, each with different expected signal and background rates. In each category, signal and background events are further separated pioneering a multivariate approach that combines a matrix element method with machine learning techniques (e.g. boosted decision trees and deep neural networks). More data are needed to possibly claim an observation of the  $tt+H(\rightarrow bb)$  process. The YIG has also analyzed the 13 TeV data collected in 2017 ( $L = 41\text{fb}^{-1}$ ) by CMS with a new pixel detector and combined the 2016 and 2017 datasets to increase the expected signal significance [4]. The result was released for the LHCP2019 conference in May 2019. In parallel, the effort has started to analyze the full Run2 dataset.

In addition, work is ongoing together with theorists (S. Moch (U. Hamburg), A. Ferroglia (City Tech., New York), A. Broggio (Tech. U. Munich)) has been established to provide the state-of-the-art of  $tt+H$  predictions.

- **First observation of the  $tt+H$  process in CMS.** The above mentioned  $tt+H(\rightarrow bb)$  analysis performed by the YIG contributed to the first ever observation of the  $tt+H$  process [5]. The ATLAS and CMS experiments independently observe a significant excess in data over background which is compatible with the SM prediction of the  $tt+H$  signal, when the measurements of the different individual decay channels using full Run1 and Run2 (up to 2017) data are combined. In a statistical analysis, each experiment disfavours the background-only hypothesis by at least 5 standard deviations, thereby claiming observation of the  $tt+H$  production mode of the Higgs boson at the LHC. Moreover, the  $tt+H(\rightarrow bb)$  analysis also contributed to the first observation of the Higgs boson decaying into  $b$  quarks ( $H\rightarrow bb$ ) in CMS [6] (also reported independently by ATLAS), achieved by the combination of  $H\rightarrow bb$  results in different Higgs boson production modes.

Within the precision of these measurements, the prediction of the top-Higgs Yukawa coupling and the mechanism giving mass to fundamental particles is confirmed. Analyzing more LHC data will allow ATLAS and CMS to improve the sensitivity and perform even stricter validation of the SM, where any deviation would hint of new phenomena.

### **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.

Following on from preliminary exploratory studies, hardware design and procurement and initial tests of core techniques performed in 2016-2017, in early 2018 the first prototype assemblies were produced within the design specifications. In March 2018, these prototypes, along with extensive technical details and fully costed automated assembly setup were presented to the CMS collaboration at the CMS tracker week at CERN.

As a result of this presentation, Prof. Ulrich Heinz and colleagues (Brown Uni, US) expressed interest in commissioning an automated assembly setup at their institute.

In June 2018, Prof. Heinz visited DESY where the automated assembly was demonstrated and collaboration between Brown and DESY towards the common goal of automated module assembly was established. As Brown will assemble modules of different thickness with respect to the DESY, small modifications to the assembly tooling were necessary.

In particular, the assembly platform upon which allows precise positioning and vacuum fixing of module components was re-designed to allow assembly of all module thicknesses and hence facilitate the replication of the automated assembly at other CMS modules production sites. Throughout summer 2018, the principal hardware components of the assembly setup were migrated so that development could continue in the DESY (Detector Assembly Facility, DAF) where module production will ultimately take place. As previous development had proceeded with a motion stage used in another DESY lab space.

The procurement, installation and commissioning of motion stages, control PC, air-cushioned lab tables was undertaken and completed by autumn 2018. In parallel, a DESY technician was integrated into the project to operate the auto-assembly during the module pre-production and production phases. A crucial improvement in the automated gluing of the baseplate to pixel sensor as part of the assembly was achieved with a summer student.

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

#### Dr. M. Aldaya:

- Co-coordinator of the CMS Top Physics Analysis group (L2) (started: 01.09.2017)
- 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 Jul 2014)
- Reviewer for J. High Energy Phys. (since Jan 2018)
- Organizing Committee member of the "Top Quark Physics at the Precision Frontier", Fermilab (Chicago, US), May 2019
- International Advisory Committee member of the "12th International Workshop on Top Quark Physics (TOP2019)", (Beijing, China) Sep 2019
- Co-chair and organizing committee of the "CMS Top Workshop 2018", CERN (Geneva, Switzerland), Nov 2018

- Organizing Committee member of the "Top Quark Physics at the Precision Frontier", (Chicago, US), Jan 2018
- Organizing Committee member of the "CMS Heavy Flavour Tagging Workshop 2018", (Brussels, Belgium), Apr 2018
- International Advisory Committee member of the "11th International Workshop on Top Quark Physics (TOP2018)", (Bad Neuenhar, Germany) Sep18
- Co-chair and organizing committee of the "CMS Top Workshop 2018", CERN (Geneva, Switzerland), Nov18

Dr. C. Diez Pardos:

- Co-coordinator of the CMS Top Mass subgroup (L3) (01.09.2016 - 31.08.2018)
- Co-coordinator between the Top Quark Physics Analyses and the Trigger Studies groups in CMS (01.04.2016 - 31.12.2018)
- Co-coordinator of the ttHbb working group at CMS (01.09.2017 - 30.11.2018)
- Co-coordinator of the CMS Top-Higgs Forum (01.09.2016 - 31.08.2018)
- Member of the CMS Analysis Review Committee (editorial board) (until 31.12.2018)
- Reviewer for Eur. Phys. Journal C (since Nov 2016)

Mr. Andrej Saibel:

- Contact person between the Higgs 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. There was 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 position was tenured by DESY in July 2017 after the positive evaluation in May 2017. There are no ongoing negotiations for a W2/W3 professorship.

#### 7) Teaching Activities of the Group Leader

There have been no teaching activities by the group leader due to her CMS L2 coordination position.

#### 8) Publications of the Group

**Public presentations by the group members:**

- J. Keaveney, *Results on top quark physics from ATLAS, CMS and LHCb*, invited talk at Kruger2018: Discovery Physics at the LHC, Kruger National Park (South Africa), 3 – 7 Dec 2018
- J. Keaveney, *Recent differential ttbar measurements in CMS*, parallel talk at Terascale18: Terascale Alliance Annual Meeting, DESY Hamburg (Germany), 26 – 28 Nov 2018

- A. Saibel, *Differential  $tt+bb$  cross section measurements at 13 TeV in leptonic final states*, invited plenary talk at CMS TOP Group Workshop 2018, CERN (Switzerland), 6 – 7 Nov 2018
- J. Keaveney, *CMS Highlights*, Report to the 86th Physics Research Committee, Zeuthen (Germany), 16 Oct 2018
- M. Aldaya, F. Canelli, *TOP PAG planning for full Run2*, plenary talk at CMS Week, Budapest (Hungary), 2 Oct 2018
- A. Saibel, *Search for  $ttH$ ,  $H \rightarrow bb$  decays using the full 2016 data sample*, poster at TOP2018: 11th International Workshop on Top Quark Physics, Bad Neuenahr (Germany), 16 – 21 Sep 2018
- C. Diez Pardos, *Measurements of  $ttH$  production*, parallel talk at ICHEP2018: 39th International Conference on High Energy Physics, Seoul (Korea, Republic Of), 4 – 11 Jul 2018; proceedings: CMS CR-2018/346
- J. Keaveney, *Automated Silicon Module Assembly*, parallel talk at 4th Matter and Technologies Annual Meeting, Berlin (Germany), 12 – 14 Jun 2018
- C. Diez Pardos, *Observation of Top Quark Pair Production in Association with a Higgs Boson*, seminar at DESY, Hamburg and Zeuthen (Germany), 5 – 6 Jun 2018
- C. Diez Pardos, *Recent  $ttH/tH$  results from CMS*, plenary talk at Benasque-Higgs2018: Higgs Toppings Workshop - Probing Top-Higgs Interactions at the LHC, Benasque (Spain), 27 May – 2 Jun 2018
- J. Keaveney, *Searches for new physics in the higgs, top and electroweak sector*, plenary talk at Alps2018: Third Alpine LHC Physics Summit, Obergurgl (Austria), 15 – 20 Apr 2018
- C. Diez Pardos, *Top Quark Physics at the LHC*, invited talk (Hauptvortrag) at DPG2018: Frühjahrstagung der Deutschen Physikalischen Gesellschaft - Teilchenphysik, Würzburg (Germany), 19 – 23 Mar 2018
- A. Saibel, *Differential cross section measurement of top quark pair production with associated bottom quarks in the dilepton channel at 13 TeV*, parallel talk at DPG2018: Frühjahrstagung der Deutschen Physikalischen Gesellschaft - Teilchenphysik, Würzburg (Germany), 19 – 23 Mar 2018

**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 normalized differential  $tt$  cross sections in the dilepton channel from  $pp$  collisions at  $\sqrt{s} = 13$  TeV*, J. High Energy Phys. 04 (2018) 060, arXiv:1708.07638 [hep-ex]
- [2] CMS Collaboration, *Measurements of  $t\bar{t}$  differential cross sections in proton-proton collisions at  $\sqrt{s} = 13$  TeV using events containing two leptons*, J. High Energy Phys. 02 (2019) 149, arXiv:1811.06625 [hep-ex]
- [3] CMS Collaboration, *Search for  $ttH$  production in the  $H \rightarrow bb$  decay channel with leptonic  $tt$  decays in proton-proton collisions at 13 TeV*, J. High Energy Phys. 03 (2019) 026, arXiv:1804.03682 [hep-ex]
- [4] CMS Collaboration, *Search for  $ttH$  production in the  $H \rightarrow bb$  decay channel with leptonic  $tt$  decays in proton-proton collisions at 13 TeV*, CMS Physics Analysis Summary CMS-PAS-HIG-18-030 (2019)
- [5] CMS Collaboration, *Observation of Higgs boson decay to bottom quarks*, Phys. Rev. Lett. 121 (2018) 121801, arXiv:1808.08242 [hep-ex]
- [6] CMS Collaboration, *Observation of  $ttH$  production*, Phys. Rev. Lett. 120 (2018) 231801, arXiv:1804.02610 [hep-ex]

Other publications with important contributions from the YIG  
(preliminary public results that are superseded by the corresponding journal publication are not included)

- CMS Collaboration, *Measurement of the inclusive  $tt$  cross section in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV using final states with at least one lepton*, J. High Energy Phys. 03 (2018) 115, arXiv:1711.03143 [hep-ex]
- CMS Collaboration, *Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, Eur. Phys. J. C 78 (2018) 140, arXiv:1710.10614 [hep-ex]
- CMS Collaboration, *Combination of inclusive and differential  $tt$  charge asymmetry measurements using ATLAS and CMS data at  $\sqrt{s} = 7$  and  $8$  TeV*, J. High Energy Phys. 04 (2018) 033, arXiv:1709.05327 [hep-ex]

As coordinator of the CMS Top Quark Physics Group since Sep 2017, the YIG leader is directly responsible (co-editor, internal referee) for 15 additional journal publications (<http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html>), and 6 additional public results (<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html>), among which are:

- CMS Collaboration, *Measurement of  $t\bar{t}$  normalised multi-differential cross sections in  $pp$  collisions at  $\sqrt{s} = 13$  TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions*, arXiv:1904.05237 [hep-ex] (submitted to Eur. Phys. J.)
- CMS Collaboration, *Observation of single top quark production in association with a Z boson in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, Phys. Rev. Lett. 122 (2019) 132003, arXiv:1812.05900 [hep-ex]
- CMS Collaboration, *Measurement of  $t\bar{t}$  production cross section, the top quark mass, and the strong coupling constant using dilepton events in  $pp$  collisions at  $\sqrt{s} = 13$  TeV*, Eur. Phys. J. C 79 (2019) 368, arXiv:1812.10505 [hep-ex]

Other publications with important contributions from the YIG  
(preliminary public results that are superseded by the corresponding journal publication are not included)

- CMS Collaboration, *Measurements of the top quark polarization and  $t\bar{t}$  spin correlations in dilepton final states at  $\sqrt{s} = 13$  TeV*, CMS Physics Analysis Summary CMS-PAS TOP-18-006 (2019), journal publication in preparation
- CMS Collaboration, *Search for standard model production of four top quarks in final states with same-sign and multiple leptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, CMS Physics Analysis Summary CMS-PAS TOP-18-003 (2019)
- CMS Collaboration, *Constraining the top quark Yukawa coupling from  $t\bar{t}$  differential cross sections in the lepton+jets final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, CMS Physics Analysis Summary CMS-PAS TOP-17-004 (2019)

#### **Dissertations:**

M. Savitskyi, *Measurements of differential cross sections for  $tt$  production in proton-proton collisions at  $\sqrt{s} = 13$  TeV using events containing two leptons with the CMS experiment*, University of Hamburg, June 2018, PhD Thesis, DESY-THESIS-2018-020

<b>9) External Funding</b>

<b>10) Patent Applications</b>
<i>No. of pending/granted patents</i>

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