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Quest for a Top Quark Partner and Upgrade of the Pixel Detector Readout Chain at the CMS

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Final Report

1 Description of accomplishments

List of people working on this research activity

- ◇ Andrew Ivanov, PI.
- ◇ Sadia Khalil, postdoc (until 2016, with additional support from LPC Fellowship).
- ◇ Nikoloz Skhirtladze, postdoc (2014-2017).
- ◇ Atanu Modak, postdoc (2017-present).
- ◇ Russell Taylor, engineer (supported by US CMS).
- ◇ Mikhail Makouski, graduate student (graduated in 2015).
- ◇ Rachitha Mendis, graduate student (2015-present).
- ◇ Tyler Mitchell, graduate student (2016-present).
- ◇ Undergraduate students: Justin Raybern, Wyatt Behn, Alex Armstrong, Amali Priyanka, Branden Schneider, Timothy Baker, Ramiro Torres (supported by KSU Physics Department and NSF REU).

During the reported period the K-State team under Ivanov's supervision included three postdocs: Khalil, Skhirtladze and Modak, three graduate students: Makouski, Mendis and Mitchell, and several undergraduate students, supported by NSF and Ivanov's start-up funds. For part of the time Khalil, partially supported with the LPC Fellowship, overlapped with Skhirtladze. In 2016 Khalil moved to another postdoc position with University of Kansas. Skhirtadze left physics and moved to industry, and was replaced by Modak. Makouski received his Ph.D. on the $t\bar{t}\gamma$ cross section measurement in 2015. Mendis completed his physics analysis on searching for vector-like quarks in opposite-charge dilepton events and will graduate in 2019. Mitchell joined the group, as an undergraduate, and is currently working on the $H \to \tau\tau$ cross section measurement.

The work of the Ivanov's research group resulted in 8 scientific publications [3-10] with one more physics result [2] approved by the CMS collaboration, the publication for which is in preparation for submission to

the EPJC journal, and one instrumentation paper [1] in preparation for submission to JINST. The Ivanov's group performed the first measurement of the $t\bar{t}\gamma$ cross section at CMS (Makouski's Ph.D. thesis) by developing a novel method, which is now used in the updated measurements of the $t\bar{t}\gamma$ cross section in the Top group; performed extensive program on searches for vector-like quarks in a variety of different channels, with one third of CMS physics results on vector-like heavy fermions being co-authored by K-State group members; as well as performed several non-conventional searches for super-symmetry investigating stealth and R-parity violation SUSY scenarios. Ivanov and Khalil convened the Very Heavy Fermions group from 2014 to 2018. K-State group members also had a number of other positions within the Beyond 2 Generations physics analysis group.

The Ivanov's group made major contributions to the data acquisition system for the Phase 1 Upgrade of the pixel detector, by developing the test-stand infrastructure for testing TBM chips, performing the testing of all of TBM chips used in Phase 1 pixel detector, as well as developing pixel FEC firmware, and commissioning the Phase 1 pixel detector at CERN. The K-State team under Ivanov's leadership is now active in the pixel detector operations with Modak serving as a pixel DAQ co-convener, and being pixel DAQ expert on-call. The group is also engaged in the Phase 2 Upgrade with Ivanov serving as a L3 project manager responsible for the high-luminosity pixel detector electronics, and Taylor developing the test system for the Phase 2 pixel modules.

2 Physics Analyses

The main focus of the physics program of the K-State group under Ivanov's leadership is a search for a partner of the top quark that can counter-balance the top quark term in the radiative corrections to the Higgs mass and thereby resolve the mass hierarchy problem. The K-State group has been active in the Top, B2G and SUSY physics groups at CMS, and performed a number of analyses in the area of the top quark physics and searches for the beyond-standard-model physics in $t\bar{t}$ final states.

Searches for Vector-like Quarks

K-State group performed a comprehensive program on searches for vector-like quarks. Vector-like quarks appear in many new physics scenarios. They can induce electroweak breaking and cancel quadratically divergent corrections to the Higgs mass. This mechanism is realized in composite Higgs, little Higgs and extra dimensions models. In these scenarios a large mixing to third generation of standard model (SM) quarks is expected, hence the name "top partners" appears in this context. Extra heavy quarks can be pair produced at LHC through their gauge couplings to gluons or singly via the electroweak coupling, and they subsequently decay into ordinary quarks plus a Higgs or a gauge boson. K-State group performed searches for up-type T and down-type B quarks, as well as for light-flavor partners Q exploring various decay channels.

The search for the up-type T quark was performed in the lepton plus jets channel by focusing on the $T \to bW$ decay mode, which is similar to the SM top quark decay. The kinematic reconstruction of the $T\bar{T} \to bW\bar{b}W \to \ell\nu + 4$ jets was performed using an algorithm similar to the top quark mass reconstruction method. As T quark is expected to be much heavier than the SM top, this algorithm has been extended to include boosted hadronically decaying W bosons, where the identification of boosted W was performed using jet substructure techniques. The sub-jets of the W bosons were reconstructed using the grooming algorithm, and served as an input into the T quark mass reconstruction fit. The physics analysis using this technique together with other T searches has been published in the CMS Run 1 legacy paper [9], and the improved version of it using the dataset collected in 2016 at $\sqrt{s} = 13$ TeV, as a stand-alone paper [3]. The existence of T quarks with masses below 1.3 TeV has been excluded at 95% C.L.

The kinematic reconstruction technique has been extended and applied for searches for the vector-like light-flavor partners Q decaying into a light-flavor quark plus a SM boson: W, Z or Higgs. These results are also applicable for top partners having substantial mixture with the first and second generation SM quarks. To improve purity of the signal events the quark-gluon discriminant has been applied for Q decay products. These

results were combined with searches in other event signatures, such as di-lepton and multi-lepton, and were published in PRD [4]. The light-flavor partners with masses up to 0.8 TeV have been excluded at 95% C.L.

Several searches were also performed for the bottom quark partner B. The B quark can form doublet with T, or can appear as a singlet. The searches were performed using the lepton plus jets channel [8], whereas the latest result explored the di-lepton signature [2], where the sensitivity to new physics has been improved by using both boosted SM boson candidates, tagged with jet substructure techniques, and resolved candidates, tagged by dedicated algorithms developed in this analysis. This analysis is a Mendis Ph.D. thesis topic, scheduled for graduation in spring 2019. The B quarks with masses below 1.2 TeV have been excluded in these searches.

In addition to pair-production searches, we searched for singly-produced quarks. Mixings of these exotic heavy quarks with SM quarks will result in flavor-changing-neutral-currents, which are significantly constrained by a number of observations. The weakest constraint is for (YB) doublet, where Y is an exotic top partner with a charge of 4/3. We performed a search for singly-produced Y quark using early Run 2 data collected in 2015 in the lepton plus jets channel, and set the first limits on the electroweak couplings of the Y quark [5].

Searches for SUper-SYmmetry

CMS has a large physics program on searches for super-symmetry (SUSY). Conventional SUSY searches exploit event signatures with large missing transverse energy. However, there are scenarios, where the decays of super-symmetric quarks will result in event signatures with small missing E_T. In this case a SUSY signal can be buried under large SM background, and can escape its discovery. One such scenario can be realized when the mass spectra of super-symmetric particles are compressed, so called "Stealth SUSY". Another scenario is when the R-parity is violated. In this scenario there is no LSP, and all super-symmetric particles decay to lighter SM particles.

To address the first scenario we performed a search for super-symmetric quark decaying as $\tilde{q} \to q\tilde{\chi}_1 \to q(W/Z)gg\tilde{G}$. The decay products from heavy $\tilde{q}$ have higher transverse momenta compared to the SM processes, and the search is performed using the fit to the S_T, scalar sum of the transverse momenta of all decay products, as a function of the jet multiplicity. Since the jet multiplicity spectrum is not reliably modeled by Monte Carlo simulation, a data-driven technique has been developed to extrapolate the S_T spectrum from the lower jet multiplicity bins. This result has been published in PLB [10].

To explore the second scenario we performed a search for the RPV stop quark $\tilde{t} \to bjj\ell$ decays and set the limits on LQD couplings in the RPV Lagrangian. The stop decaying through a LQD RPV vertex produces cascades, which leads to same-flavor, opposite-charge dilepton + jets. The analysis strategy is similar to the Stealth SUSY analysis, but targeting higher jet multiplicity bins, ≥ 5 jets. In this result, we excluded stop quark masses below 0.9-1.0 TeV [7].

Measurement of the $t\bar{t} + \gamma$ Production Cross Section

The measurement of the production cross section of the top quark pairs associated with a photon provides a measurement of the top quark charge and allows to probe the top quark electroweak couplings. This analysis was also a step towards new physics searches involving both top quarks and photons in the final state. The result is a topic of Makouski Ph.D. thesis. Makouski developed a data-driven technique to measure the photon purity using the fit to the charged hadron isolation of a photon. Next, Makouski developed a technique to constrain the dominant background, $W\gamma$ production, with a real photon in the final state. The $W\gamma$ contribution was measured in-situ by the fit to the M3 distribution, where M3 variable represents an invariant mass of the triplet of jet with the maximum vector p_T sum. The M3 distribution has a distinct peak near the top quark mass for $t\bar{t}$ events, which allows to distinguish $t\bar{t}$ from other backgrounds. The simultaneous two-dimensional fit to the M3 and a charged hadron isolation allows to extract $t\bar{t} + \gamma$ with reduced systematic uncertainty, as compared to previous methods studying $t\bar{t} + \gamma$ production. This result has been published in JHEP [6].

3 Phase 1 and Phase 2 Pixel Detector Upgrades

The original CMS pixel detector operated until 2016, would not have sustained the high luminosity conditions expected in LHC after 2017 reaching the maximum throughput rate for data links of the innermost layer. The Phase 1 pixel detector with a modified data acquisition system (DAQ) was installed during an extended technical stop in the beginning of 2017. It features a fully digital readout system with a new back-end electronics, and is expected to deliver high performance tracking in the higher luminosity environment. Two serial output data streams of groups of digital ROCs are multiplexed by the token-bit manager chip (TBM). The output signal of the TBM is converted to an optical signal and transmitted to back-end electronics. The control part of the system is performed by the Front-End Controller (FEC). The pixel FEC distributes clock, trigger and fast signals to the pixel modules and is responsible for programming ROC and TBM registers.

K-State group designed a TBM test board, constructed a test-stand for evaluating performance of the TBM chip design, and performed production testing of TBM chips, which were later installed in the Phase 1 pixel detector. Ivanov's group also developed the pixel FEC firmware and commissioned the pixel DAQ system at CERN prior to the start of the data taking in 2017.

TBM Testing

The KSU HEP group receives a technical support from the KSU - Electronics Design Lab (EDL). The engineering support has been funded with the NSF MRI grant, as well as with the Phase 1 Pixel Upgrade project funds through Fermilab. Engineer Russell Taylor developed a test board for testing performance of the TBM and Gatekeeper chips.

The TBM represents a radiation-hard integrated circuit that controls the readout of group of ROCs. The Phase 1 pixel TBM replaced the analog-encoded readout system with an all-digital one. It consists of two cores outputting the serial data at 160 MHz, which are combined by DataKeeper block into a 400 MHz optical stream transferred downstream.

During testing several TBM design flaws have been identified in the PLL implementation and in the Data-Keeper block of the chip which led to occasional data errors, and which were fixed in the following iterations of the chip design. Taylor also designed a probe card to perform the production wafer testing of the TBM and Gatekeeper chips. Makouski wrote the GUI software interface for programming the inputs sent to TBM through the ROCs, and analyzing the output data stream. Taylor, Ivanov and Makouski developed the protocol for testing TBM chips, which included critical aspects of TBM operations, such as basic read-out operations as well as tests on degradation due to radiation, etc. The protocol test features have been integrated into the GUI interface by Makouski and Raybern.

About 12000 TBM and Gatekeeper chips on wafers were tested using K-State Cascade probe station with help from a team of undergraduate students. Skhirtladze developed infrastructure to automatically integrate the test results into the CMS tracker database, implemented in the SQL. The tested wafers were further shipped to Fermilab for dicing, and the diced chips were distributed to different locations world-wide for construction of pixel modules.

Pixel Front-End-Controller (FEC) Firmware Development

The pixel DAQ backend electronics in Phase 1 is based on the μTCA architecture. K-State team installed a test-stand using a μTCA crate populated with FC7 boards designed by Imperial College, London. The FC7 is a double-width board holding a Xilinx Kintex 7 FPGA and with two mezzanine card (FMC) slots hosting high-speed optical transceivers. The block of 4 Gb DDR3 RAM for data buffering supports a transfer rate of 30 Gbps. The application specific FMCs and firmware make a FC7 into Front-End Driver or Front-End-Controller.

The pixel FEC firmware design was accomplished by Taylor using Xilinx Vivado development tools. For the

testing purposes a Linux computer was configured to communicate with FC7 boards. Ivanov and Skhirtladze developed testing software to establish FC7 - computer communications based on the IPBus package. Skhirtladze also developed low-level C++ libraries based on the μHAL package for establishing a communication to the pixel FEC boards and running basic functionality commands. These libraries were further integrated into the official pixel online release.

In 2016 Skhirtladze and Ivanov, on sabbatical, moved to CERN and integrated the pixel FEC board into the μTCA test-stand setup at Tracker Integrated Facility (TIF) in CERN. This test-stand connected to a 14-channel stack of pixel models, with FEDs in the same μTCA crate receiving the data stream from pixel ROCs and TCDS cards, responsible for providing the clock and trigger information to the front-end electronics, was a more realistic representation of the working system. Several revisions of the pixel FEC firmware were implemented and tested towards establishing the desired performance and communication with the CMS DAQ system via the AMC13 controller. After successful tests at TIF, the pixel FEC boards were installed and connected to the assembled pixel detector at P5. Ivanov and Skhirtladze participated in installation and commissioning of the pixel DAQ system at P5.

Pixel Detector Operations and Other CMS Service Activities

In 2017 Modak and Taylor implemented additional improvements to the pixel FEC firmware and software by taking advantage of DDR3 memory on FC7 cards and storing configuration data locally on the FC7 card. Avoiding a step of fetching the configuration data from the remote server significantly reduced the pixel detector configuration time, as well as reduced the deadtime during the data-taking due to much faster soft error recovery. This feature has been commissioned and used since spring 2018.

Modak currently serves as co-convener of the pixel DAQ group. He is responsible for the official version release of the pixel online software (POS), and implemented many improvements in POS to establish more smooth and efficient data taking. In particular, he fixed implementation of the Tracker FEC to establish more robust communication, improved the front-end programming of ROCs to reduce noise, improved the configuration of FEDs, and implemented improvements to reduce errors at the configuration stage. Modak served as a pixel detector and pixel DAQ expert on-call for 17 weeks in 2018 providing daily operation feedback, taking regular calibrations, monitoring the health of the detector, diagnosing and fixing the problems. Modak tested faulty DAQ hardware components in TIF, contributed to testing pixel FED firmware in preparation for Heavy Ion run, and served as a tutor at the pixel DAQ workshop for hands-on sessions.

Mendis serves as a E/Gamma group validator for electrons. His role is validating the new software releases for all electron related variables. He also performs validation of the electron variables upon introduction of new corrections, such as ECAL pedestals, pulse shapes and etc. Mitchell plays a similar role, being a validator of the new software releases for the boosted objects used in the B2G physics group.

Mendis performed the forward hadronic calorimeter (HCAL) readout studies to study the PMT gains using 2017 and 2018 data, and served as an offline validator at FNAL ROC to ensure the smooth HCAL detector data taking.

Phase 2 Pixel Detector Upgrade

Ivanov serves as a US CMS L3 project manager, responsible for electronics of the HL-LHC forward pixel detector. The Phase 2 pixel detector upgrade is funded through the NSF MREFC. In December 2017 the project successfully passed the preliminary design review. As a part of this project, Taylor designed a FMC test card for the Phase 2 pixel module testing, capable of communicating with up to four RD53A pixel readout chips, which will be employed in the pixel module test-stands world-wide. The FMC is hosted by the FC7 board, for which Taylor is also developing the RD53A read-out and testing firmware blocks in collaboration with colleagues from CERN, Budapest and Strasbourg.

4 Leadership positions, CMS operation and support activities at CMS

- ◇ Andrew Ivanov, US CMS L3 project manager, responsible for electronics of High-Luminosity pixel detector upgrade (2016-present).
- ◇ Andrew Ivanov, co-convener of the CMS Very Heavy Fermions physics group (L3 position, 2016-2018).
- ◇ Andrew Ivanov, Monte Carlo contact for the CMS Beyond 2 Generations physics group (2012-2015).
- ◇ Atanu Modak, co-convener of Pixel tracker Data Acquisition group (2018-present).
- ◇ Atanu Modak, Pixel DAQ expert on-call (2017-present).
- ◇ Nik Skhirtladze , Physics Performance and Datasets contact for the CMS B2G physics group (2014-2015).
- ◇ Sadia Khalil, co-convener of the CMS Very Heavy Fermions physics group (L3 position, 2014-2016).
- ◇ Sadia Khalil, Physics Performance and Datasets contact for the CMS B2G physics group (2013-2014)
- ◇ Sadia Khalil , E/Gamma contact for the CMS B2G and Top quark physics analysis groups (2013-2014).
- ◇ Andrew Ivanov, Atanu Modak, Nik Skhirtladze, Sadia Khalil, pixel DOC shifts at CMS (2015-2018).
- ◇ Rachitha Mendis, Data Quality Monitoring contact in the E/Gamma objects group (2016-present).
- ◇ Rachitha Mendis, HCAL shifts at FNAL ROC (2016-2018).

5 Publication list with acknowledged DOE support

- ◇ [1] W. Adam *et al.* [CMS Phase 1 Pixel Collaboration], "The Data Acquisition and Control System for the CMS Phase 1 Pixel Detector", under the CMS Tracker Group review, to be submitted to JINST.
- ◇ [2] A. Sirunyan *et al.* [CMS Collaboration], "Search for vector-like quarks in events with two oppositely charged leptons and jets in proton-proton collisions at $\sqrt{s} = 13$ TeV", in the Final Review by the CMS Collaboration, to be submitted to EPJC.
- ◇ [3] A. Sirunyan *et al.* [CMS Collaboration], "Search for pair production of vector-like quarks in the $bW\bar{b}W$ channel from proton-proton collisions at $\sqrt{s} = 13$ TeV", Phys. Lett. B **779** (2018) 82.
- ◇ [4] A. Sirunyan *et al.* [CMS Collaboration], "Search for vector-like light-flavor quark partners in proton-proton collisions at $\sqrt{s} = 8$ TeV", Phys. Rev. D **97**, 072008 (2018).
- ◇ [5] A. Sirunyan *et al.* [CMS Collaboration], "Search for single production of vector-like quarks decaying into a b-quark and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV", Phys. Lett. B **772** (2017) 634.
- ◇ [6] A. Sirunyan *et al.* [CMS Collaboration], "Measurement of the semileptonic $t\bar{t} + \gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV", JHEP 10 (2017) 006.
- ◇ [7] V. Khachatryan *et al.* [CMS Collaboration], "Search for R-parity violating decays of a top squark in proton-proton collisions at $\sqrt{s} = 8$ TeV", Phys. Lett. B **760** (2016) 178.
- ◇ [8] V. Khachatryan *et al.* [CMS Collaboration], "Search for pair-produced vectorlike B quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV", Phys. Rev. D **93**, 112009 (2016).
- ◇ [9] V. Khachatryan *et al.* [CMS Collaboration], "Search for vectorlike charge 2/3 T quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV", Phys. Rev. D **93**, 012003 (2016).
- ◇ [10] V. Khachatryan *et al.* [CMS Collaboration], "Search for stealth supersymmetry in events with jets, either photons or leptons, and low missing transverse momentum in pp collisions at 8 TeV", Phys. Lett. B **743** (2015) 503.