Final Report: Triggering on New Physics with the CMS Detector

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1 Introduction

This report summarizes the research activities undertaken by our group led by Prof. Tulika Bose during the May 1st, 2013 - March 31st, 2016 grant period. We continue to make significant contributions to the Compact Muon Solenoid (CMS) trigger and to searches for new physics. We also hold major positions of responsibility within the CMS experiment. Bose was appointed as the Trigger Co-coordinator of the CMS Experiment for a two year term starting September 2014. CMS is a $\approx$ 5000 member collaboration and is headed by a group of about fifty people (CMS Management Board) responsible for directing the CMS experiment and for drawing up policy. All important matters of scientific and technical nature, safety, organisation and finance are discussed by this group which is ultimately responsible for various tasks and projects within the experiment. The Trigger Coordinator is a member of this select group and oversees the activities of the CMS Trigger Studies group that is responsible for providing triggers that are tailored for the physics priorities of the experiment. Prior to taking up this position, Bose served as the co-convener of the CMS Beyond Two Generations (B2G) Resonances group from July 2012 - August 2014. Bose was also awarded the 2014 CMS Distinguished Researcher award in recognition of her work on CMS. Bose served as the USCMS Physics Liaison for 2012-2014 and was responsible for representing USCMS physics interests to the funding agencies and also coordinating physics activities within USCMS. In April this year, Bose was selected to serve as the L2 co-convener of the B2G physics analysis group; her two year term starts in September 2016 upon the completion of her term as CMS Trigger Co-coordinator.

Postdoctoral research associate Aram Avetisyan (supported partially by this grant) served as the convener of the Field Operations Group within the CMS Trigger Studies Group up until August 2015. Avetisyan is the recipient of the 2013 and 2014 CMS Junior Distinguished Researcher Award. This is awarded annually to some of the top CMS postdoctoral research associates. Graduate students Cory Fantasia and David Sperka successfully defended their theses during the 2013-2014 academic year. Graduate student Dylan Rankin (supported upon Sperka's graduation) serves as the Trigger Convener for the B2G group. Graduate student Clint Richardson (supported upon Cory Fantasia's graduation) served as the Missing E_T expert for the Exotica group and is responsible for measuring the CPU performance of the CMS High-Level Trigger (HLT). He is the recipient of the 2014 Fundamental Physics Scholarship. This CMS-wide competition typically selects an outstanding young CMS researcher each year and provides them a special opportunity to enhance their research goals by providing research support opportunities as well as financial support to facilitate an extended stay of one year at CERN. He is also the recipient of the 2015 CMS Achievement award for his contributions to the CMS HLT. This award is given annually to the most deserving graduate students and postdocs contributing to the sub-detector projects and data-taking/operations. Richardson was one of only six CMS graduate students who got the award this particular year.

2 Trigger

Our group at Boston University has played a leading role in the CMS Trigger since the start of Run I. With the start of Run 2 imminent, in summer 2014, Bose was asked to serve a two-year term as CMS Trigger Coordinator. Bose accepted this challenge and assumed overall responsibility for the successful operation of the CMS trigger. Her work involves coordinating the work done within the CMS Trigger Studies Group (TSG) in collaboration with the Level-1 Trigger group. The tasks overseen include designing trigger menus for higher luminosities, trigger code development, evaluating trigger performance and trigger menu deployment. Since the nature of the work demands extended presence at CERN for maximal effectiveness, Bose procured funds for a teaching buyout for Fall 2015 from USCMS Operations/DOE allowing her to move to CERN prior to the start of Run 2 data-taking. During Spring 2016, Boston University agreed to have her continue to be based at CERN and teach students at BU via a remote classroom setup.

Based at CERN since June 2015, Bose has successfully seen to the restart of trigger operations for Run 2 both in 2015 and 2016. The TSG, led by Bose, has ensured the successful operation of the HLT during commissioning runs as well as the 50 ns and 25 ns collision runs. Many different trigger menus have been designed covering a range of LHC scenarios: luminosities ranging from 5×10^{33} cm^{-2} s^{-1} and pileup of about 20 to 1.4×10^{33} cm^{-2} s^{-1} and pileup of about 45. Some of the highlights include the extensive use of Particle-Flow techniques at the HLT, use of optimized techniques for out-of-time pileup mitigation and the use of improved conditions for alignment and calibration. Dedicated menus have also been deployed for special scenarios including extended periods of running in zero magnetic field conditions and also special low pileup runs for heavy-ion and forward physics.

Research Associate Avetisyan served as the co-convener of the Field Operations Group (FOG) within the Trigger Coordination area for the 2013-2015 period. This is a critical position with very good visibility since the conveners are responsible for the online operation of the HLT and represent the HLT/TSG in various CMS fora. The activities overseen by Avetisyan included: expert on-call shifts, online validation, and deployment of trigger menus. He also coordinated the development and integration of online monitoring for the HLT: online DQM, CPU and rate monitoring systems. Avetisyan optimized the rate monitoring software for multithreaded performance and coordinated with various experts to make sure that the rates were correctly inserted into the CMS online database. Finally, for Run 2 trigger operations, Avetisyan continued to work on designing and implementing tools for online validation and monitoring.

Graduate student Clint Richardson is a member of the Field Operations group and holds the responsibility for evaluating and monitoring the CPU performance of all HLT algorithms. In preparation of Run 2 data-taking, Richardson evaluated the impact of pileup on the average HLT processing time. Richardson also evaluated the expected HLT performance for a number of LHC scenarios. For many of these scenarios Richardson found the average processing time to be consistent with the timing budget of the HLT filter farm. However, in the more challenging scenarios, a large fraction of the total CPU available would be needed, leaving very little room for potential increases in CPU consumption due to increased pile-up, higher luminosities or the introduction of more complicated algorithms. Richardson's work has resulted in pointing out a number of algorithms performing non-optimally and work is underway for improving their performance. Richardson's critical work on HLT performance played a big role in his being awarded the 2014 Fundamental Physics Scholarship. The funds from this scholarship enabled him to relocate to CERN in March 2015 just prior to the start of data-taking. Since then, Richardson has already established himself as an HLT on-call expert and is part of a small team of CMS-wide experts providing immediate 24/7 support for any HLT issue related to operations.

Prior to the start of Run2, our group took over the charge of implementing jet substructure techniques at the HLT for identifying boosted top quarks and W bosons. This had never before been accomplished at a hadron collider. Avetisyan and graduate students Rankin and Richardson have designed triggers that use advanced algorithms such as trimming, pruning, and filtering to reconstruct hadronic W/top decays. Rankin successfully implemented a single jet trigger using trimmed jets reconstructed with the Anti-k$_T$ algorithm and $R = 0.8$. Trimming is very effective against multijet/QCD events and pileup and Rankin's studies indicated that this trigger provided a significant rate reduction ($\sim$ 20%) over a single jet trigger with the same threshold. Rankin followed this success with the implementation of a dijet trigger also useful for a wide variety of physics signals. Our group's experience/expertise in this area is now highly regarded within CMS especially given that our work has the potential to yield inclusive triggers for boosted Higgs, top quarks, and exotic, heavy resonances thereby boosting the overall CMS sensitivity to all of these processes. Rankin was invited to present this work before a plenary U.S. CMS audience in October 2014 and also represent CMS at the BOOST conference in August 2015.

Rankin's work was greatly appreciated by the B2G physics group and he was asked to serve as their trigger convener. He holds the responsibility for reviewing the trigger strategy for all B2G analyses and actively helps other analysts develop their trigger strategy. In 2015 he collaborated with others within the B2G group to develop a suite of triggers using jet substructure techniques for a wide variety of searches ($T \to tH$, $T \to bW$, $B \to tW$). Rankin moved to CERN in March 2015 and quickly established himself as an HLT on-call expert and is part of a small team of CMS-wide experts providing immediate 24/7 support for any HLT issue related to operations.

3 Physics Analysis

Our group is involved in a variety of physics analyses where the students/postdoc are playing important roles. We are concentrating on topics that take full advantage of our group's strengths in trigger, lepton identification, jets and calorimetry as well as our considerable experience in hadron collider physics. We also work in close collaboration with the BU theory group. One of our former students, Cory Fantasia, was co-advised by Bose and her theory colleague Prof. Kenneth Lane.

3.1 Searches with top quarks and diboson resonances

Bose served as the co-convener of the "Resonances" sub-group within the "Beyond Two Generations" (B2G) physics analysis group for a period of about two years (2012-2014). The charge to her group included searches for exotic $t\bar{t}$ resonances, heavy top partners, and searches for exotic particles decaying to top and bottom quarks. Our group has a strong presence within the B2G physics group and is actively leading many of these analyses efforts. Bose will be the B2G co-convener starting September 2016.

3.1.1 Top partners

Heavy "top partners" arise in many models that attempt to solve the hierarchy problem. These top partners are expected to have masses close to the electroweak symmetry breaking scale and thus would be accessible at the LHC. They may also have exotic charge (5e/3) and in this case yield minimal/no contribution to the coupling of the Higgs boson to gluons. Searches for such top-quark partners explore parameter space that is not excluded by the recent observation of a Higgs boson with properties consistent with those of the SM Higgs particle.

Avetisyan, under Bose's mentorship, played a leading role in the 7 and 8 TeV CMS searches for a heavy top partner with charge 5/3 which decays to a top quark and a W boson. This $T_{5/3}$ can be produced via the strong interaction in conjunction with its anti-particle and their decay can result in a striking signature consisting of same-sign leptons (electrons and/or muons) and many jets.

For the $\sqrt{s} = 8$ TeV analysis, Avetisyan implemented advanced techniques in jet reconstruction for identifying boosted top quarks and W bosons from the $T_{5/3}$ decay. A "top-tagging" algorithm based on identifying jet substructure was used to reconstruct merged top jets. Jets were clustered using the Cambridge-Aachen (CA) algorithm with a distance parameter of $R = 0.8$ in $\eta - \phi$ space. Several additional kinematic requirements were imposed based on the substructure of the jet (e.g. number of subjets, mass of CA jet). The decay products of W bosons from the $T_{5/3}$ decay or from a moderately boosted top quark for which the b quark is reconstructed independently may also merge into a single jet. Avetisyan used a "jet pruning" algorithm with Cambridge-Aachen $R = 0.8$ jets as input to identify the hadronic decay of such W bosons.

On analyzing the full 8 TeV dataset, we observed no significant excess in the data above the expected standard model background. Upper bounds at the 95% confidence level were set on the production cross section of heavy top quark partners assuming a 100% branching fraction for the decay $\mathrm{T}_{5/3} \rightarrow \mathrm{tW}$ and masses below 800 GeV were excluded. This was the first limit on $\mathrm{T}_{5/3}$ production from the LHC at 8 TeV and was a significant improvement on the previous published limit of 365 GeV. In particular, Avetisyan's use of advanced jet reconstruction techniques allowed us to probe cross-sections of the $\mathrm{T}_{5/3}$ that are about 15% lower than would otherwise be possible. This analysis has been published in the Physical Review Letters [Phys. Rev. Lett. 112 112 171801 (2014].

Graduate student Clint Richardson is currently working on updating the analysis framework for this search using Run 2 data; this analysis serves as his thesis topic. A critical component of the analysis is the evaluation of the primary instrumental background arising from jets being misidentified as leptons and nonprompt leptons passing tight isolation selection criteria. The data-driven background estimation method used for the 8 TeV analysis relied on measuring the "fake" ratio in a QCD-enriched region. The data for this measurement region was collected using a couple of prescaled single lepton triggers with low thresholds. The falling p_T spectrum resulted in a small number of selected events with higher p_T leading to an increase in the statistical uncertainty of the method. Richardson has worked on adopting a trigger strategy for the Run 2 analysis that relies on a set of prescaled single lepton triggers with varying thresholds but with the same identification and isolation selection as the signal triggers. He has also optimized their requirements allowing for greater bandwidth to be allocated to these triggers during the LHC ramp-up period. This should provide the necessary statistics for an improved fake rate evaluation for Run 2. The other challenge associated with the fake rate measurement is the imperfect closure of the method. This led to a large systematic uncertainty (50%) being associated with this method. Our 8 TeV studies gave a first indication that this could be partly related to differences in the flavor composition and parton transverse momentum between the measurement region and the application region. Richardson and Avetisyan are working on verifying this for 13 TeV and are also working on understanding residual discrepancies. We expect their work to lead to a sizable reduction in the systematic uncertainty associated with the method and hence an overall improvement in the sensitivity of the analysis. Richardson is also optimizing the signal selection for higher $T_{5/3}$ masses with particular emphasis on selecting an optimal isolation criteria. A preliminary version of the Run 2 analysis was approved by CMS for public dissemination in December 2015 [CMS-PAS-B2G-15-006] and a publication is expected this year.

3.1.2 $W' \to tb$

Bose played a leading role in a novel search for W' boson resonances decaying to a top quark and a bottom quark using data collected by the D0 detector. The analysis set cross section and mass limits using advanced analysis techniques that represented a significant improvement over previously published results and the paper was published in Physical Review Letters [Phys. Rev. Lett. 100 211803 (2008)]. She used her experience with the analysis and together with former graduate student David Sperka played a major role in the CMS version of the analysis. Using 7 TeV data and the leptonic decay of the top quark, the analysis excluded masses below 1.85 TeV at the 95% condence level for a W' boson that couples to fermions with the same coupling constant as the W but to the right-handed rather than the left-handed chiral projections [Phys. Lett. B 718 1229 (2013)]. Also, for the first time using LHC data, constraints on the W' gauge coupling for a set of left- and right-handed coupling combinations (a_L, a_R) were placed. These limits represented a significant improvement over previously published results. Sperka led the effort behind the 8 TeV analysis and this resulted in a limit of 2 TeV [JHEP 05 108 (2014)]. We have recently worked on combining our result with the $W' \to tb$ all-hadronic channel; the lower limit on the mass of the right-handed W' boson increases to 2.15 TeV at 95% C.L. when both hadronic and leptonic decays are considered. Stringent limits are also set in the (a_L, a_R) plane.

Graduate student Dylan Rankin has been working on improving and optimizing the lepton+jets analysis for 13 TeV; this analysis serves as his thesis topic. In particular, Rankin has worked on incorporating improvements to lepton identification and also optimizing the signal selection for boosted topologies. A preliminary version of the Run 2 analysis was approved by CMS for public dissemination in December 2015 [CMS-PAS-B2G-15-004] and a publication is expected this year.

3.1.3 WZ cross section measurement and resonance search

Bose led this analysis effort during Run 1 with former graduate student Cory Fantasia playing a critical role. Fantasia was co-advised by BU theorist Prof. Kenneth Lane who provided critical theoretical guidance. Fantasia's thesis involved working on a generic search for exotic WZ resonances, such as ρ_{TC} of technicolor and the W' found in minimal extensions of the standard model and in higgsless models. Bose jump-started this effort in early Run 1 with Fantasia assuming a primary role in the WZ cross section measurement. Following the success of the first WZ cross section measurement, Fantasia moved on to perform a search for new exotic particles decaying to the WZ final state with electrons and muons using 5 fb^{-1} of $\sqrt{s} = 7$ TeV data collected by the CMS experiment. No significant excess was found in the mass distribution of the WZ candidates compared to the background expectation from standard model processes. The results were, therefore, interpreted in the context of different theoretical models and lower bounds at the 95% C.L. were set on the masses of hypothetical particles decaying to the WZ tri-leptonic final state. The results were subsequently published by Physical Review Letters [Phys. Rev. Lett 109 141801 (2012)].

Following Fantasia's graduation in October 2014, student Clint Richardson assumed a primary role in this analysis effort and was instrumental in seeing it through to publication. Richardson was also partially supported by Prof. Lane until March 2014 after which he was solely supported by Bose's DOE grant. Richardson was responsible for optimizing the selection criteria, measuring the trigger efficiency, and determining several of the systematic uncertainties. Richardson's optimization work led to an $\approx 15\%$ improvement in overall sensitivity. No significant excess was observed above the expected standard model background and this optimization, together with other improvements in lepton identification and reconstruction, allowed us to set very competitive exclusion limits. Assuming an extended gauge model, an expected (observed) exclusion limit of 1.55 (1.47)

TeV on the mass of the W' boson was set. Low-scale technicolor ρ_{TC} hadrons with masses below 1.14 TeV were also excluded. These exclusion limits represent a large improvement over previously published results obtained in pp collisions at $\sqrt{s} = 7$ TeV. The paper was published in Physics Letters B in January 2015 [Phys. Lett. B 740 83 (2015)].

4 Summary

The funds available from this grant were greatly instrumental in supporting our research activities over the last year. Our group has made many significant contributions to the CMS experiment, both to the CMS trigger and in physics analyses.

5 Publications

Some recent publications to which our group has made significant contributions:

1. **"Search for $W' \to tb$ in proton-proton collisions at $\sqrt{s} = 8$ TeV"**, CMS Collaboration, JHEP **1602**, 122 (2016), arXiv:1509.06051 [hep-ex].

2. **"Search for monotop signatures in proton-proton collisions at $\sqrt{s} = 8$ TeV"**, CMS Collaboration, Phys. Rev. Lett. 114, 101801 (2015), arXiv:1410.1149 [hep-ex].

3. **"Search for new resonances decaying via WZ to leptons in proton-proton collisions at $\sqrt{s} = 8$ TeV"**, CMS Collaboration, Phys. Lett. B **740** 83 (2015), arXiv: 1407.3476 [hep-ex]

4. **"Search for pair production of excited top quarks in the lepton+jets final state"**, CMS Collaboration, JHEP **06** 125 (2014), arXiv:1311.5357 [hep-ex].

5. **"Search for W' to tb decays in the lepton + jets final state in pp collisions at $\sqrt{s}$ = 8 TeV"**, CMS Collaboration, JHEP **05** 108 (2014), arXiv:1402.2176 [hep-ex].

6. **"Search for top-quark partners with charge 5/3 in the same-sign dilepton final state"**, CMS Collaboration, Phys. Rev. Lett. **112** 112 171801 (2014), arXiv:1312.2391 [hep-ex].

7. **"Inclusive search for a vector-like T quark with charge 2/3 in pp collisions at $\sqrt{s} = 8$ TeV"**, CMS Collaboration, Phys. Lett. B **729** 149 (2014), arXiv:1311.7667 [hep-ex].

8. **"Search for a W' boson decaying to a bottom quark and a top quark in pp collisions at $\sqrt{s} = 7$ TeV"**, Phys. Lett. B 718 1229 (2013), arXiv:1208.0956.

9. **"Searches for long-lived charged particles in pp collisions at $\sqrt{s}$ =7 and 8 TeV"**, CMS Collaboration, JHEP 07 122 (2013), arXiv:1305.0491.