High Energy Physics Research at the CMS Experiment

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1 Introduction

The research proposed here will focus on finding solutions to the hierarchy problem of particle physics using novel jet reconstruction techniques to reconstruct highly-boosted standard model particles such as top quarks, W/Z and Higgs bosons. This research will be critical in the next phase of Large Hadron Collider (LHC) operations to maximize the discovery potential at the Energy Frontier of particle physics.

With the discovery of a standard model (SM)-like Higgs boson at 125 GeV during the 7 and 8 TeV runs of the LHC ("Run 1") [1, 2], the focus of collider physics now turns to understanding the nature of the observed mechanism for electroweak symmetry breaking. The SM is an effective theory, and quadratically-divergent quantum-loop corrections to the Higgs mass would require an enormous degree of fine tuning, if the Higgs mass is to remain finite up to the Planck scale. This is commonly referred to as the hierarchy problem, which can be resolved by introducing contributions beyond the standard model (BSM). These BSM models must survive a myriad of precision tests of the SM (such as the recent observation of $B_s \rightarrow \mu^+\mu^-$ [3, 4]), and extensive direct searches.

Various mechanisms beyond the standard model have been proposed to resolve the hierarchy problem. Since the most divergent quantum corrections to the Higgs mass involve top quarks and SM bosons, it is natural to suppose that BSM mechanisms preferentially involve loop interactions with these particles to cancel this divergence. Two major classes of models which solve the hierarchy problem discussed above are supersymmetry (SUSY) [5, 6, 7, 8, 9] and extra dimensions (ED) [10, 11, 12, 13]. After Run 1 of the LHC, the available phase space for these models contains SM particles in the final state that are often highly Lorentz boosted.

In recent years, new jet-clustering techniques have been developed to handle highly-boosted massive SM particles [14, 15, 16, 17, 18, 19, 20, 21, 22]. Summaries of these techniques are in Refs. [23, 24]. These large jets are referred to as "boosted jets" ("boosted tops", "boosted W's", "boosted Z's", "boosted Higgs"), and they are different from jets that originate from quantum chromodynamic (QCD) processes in that they exhibit different internal structure ("substructure"), and have an intrinsic jet mass. These algorithms analyze the substructure and mass of the boosted jet to break it up into smaller "subjets" which can be analyzed at smaller angular scales, thereby allowing analysis of highly-boosted states. Figure 1 shows an event display of such a highly-boosted top quark at CMS. The blue rectangles represent the energy measured in the hadronic calorimeter, the green rectangles represent the energy measured in the electromagnetic calorimeter, and the three groups of colored lines (purple, red, and orange) represent three different subjets as measured in the tracker. Using traditional reconstruction techniques, this object would be reconstructed as a single four-vector, whereas the newer techniques involving jet substructure are able to discern the three separate subjets.

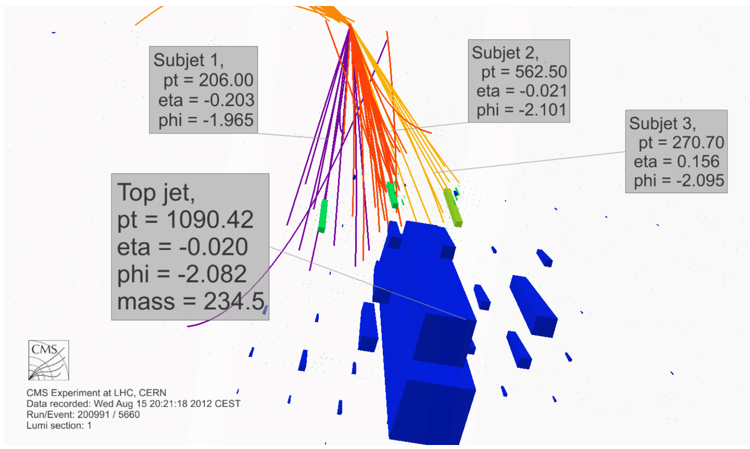

Figure 1: Event display of a highly-boosted top jet. The blue rectangles represent the energy measured in the hadronic calorimeter, the green rectangles represent the energy measured in the electromagnetic calorimeter, and the three groups of colored lines (purple, red, and orange) represent three different "subjets" as measured in the tracker.

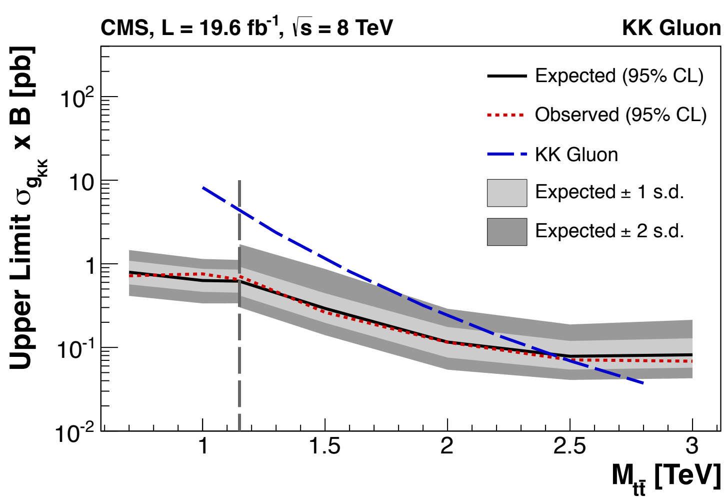

Figure 2: Limits on the mass of possible Kaluza-Klein excitations of the gluon in decays to $t\bar{t}$ pairs from a combination of results in Refs. [25, 26].

Without using these boosted-top strategies, the sensitivity of searches for particles predicted by these BSM models is reduced by a factor of ten or more, even at energies accessible during Run 1 of the LHC. For instance, Fig. 2 shows the cross-section limits for a KK gluon from the analysis in Ref [27]. At a mass of 2 TeV, the sensitivity of boosted-top techniques is a factor of 10 better than the sensitivity without using these techniques. This improvement grows even larger with the mass of the KK gluon.

2 Prior Work

2.1 Overview of Activities

Prof. Salvatore Rappoccio (tenure-track Assistant Professor) joined the Faculty at the University at Buffalo, SUNY (UB) in 2012. The UB group has an NSF grant (Award Number 1205960, July 15th 2012 - June 30th 2015) from Professors Kharchilava and Iashvili, however this was renewed one year before Prof. Rappoccio joined the Faculty and does not provide support for him or his group.

Prof. Rappoccio's group consists of Dr. James Dolen (postdoctoral fellow), Mr. Joshua Kaisen and Ms. Maral Alyari (graduate students), Mr. Brendan Smith and Mr. Jonathan Goodrum (undergraduate students, the latter supported under the "Collegiate Science and Technology Program" (CSTEP) at UB, which provides research funding for minority and disadvantaged undergraduate students). Work has already started on the proposed research using short-term startup funds. These startup funds will run out by 30-June-2014. If no funding is found, the support for Dr. Dolen, Mr. Kaisen, and Ms. Alyari will run out, and they will not be able to continue their studies.

The larger UB group consists of Profs. Kharchilava and Iashvili, two postdoctoral fellows, Dr. Ashish Kumar and Dr. Supriya Jain, and three Ph.D. students, Mr. Joseph Zennamo, Mr. Andrew Godshalk, and Mr. Jimin George. Prof. Rappoccio's group has already commenced collaboration with the teams of Kharchilava and Iashvili, specifically in the commissioning of the pixel detector.

2.2 CMS Activities

Prof. Rappoccio has played a critical leading role in implementing and understanding these jet substructure and boosted techniques at the LHC in general, and became the foremost expert of this topic at CMS. This work started while he was a postdoctoral fellow at Johns Hopkins University working under NSF Grant 1100862, and expanded greatly during his tenure at UB, based on his short-term startup funds.

Rappoccio's early studies (before collision data) and implementation of the algorithms are outlined in Ref. [17]. He has authored the first searches for new physics with collision data to be published using boosted top [28] and boosted W/Z [29] techniques anywhere in the world, as well as the first measurement of the jet mass at CMS [30]. In addition, he has contributed to several of the now-seminal review papers about the subject, which are used as standard references and benchmarks in the community at large [23, 24].

After these pioneering efforts successfully established the CMS Collaboration as a world leader in the fields of jet substructure and boosted hadronic final states, Prof. Rappoccio was made the convener of a newly-formed “Beyond Two Generations” Physics Analysis Group (B2G PAG) at CMS, which focuses on these highly-boosted final states, in particular in the top sector. In his tenure as convener since August 2012, CMS has deployed these techniques in 4 analyses of the 8 TeV data (one paper submitted [27], and several in preparation) [31, 32, 33]. Furthermore, the techniques are being adopted in four other analyses to search for other exotic signatures (including the 8-TeV continuation of Ref. [29] in Ref. [34]), as well as two analyses to search for supersymmetry.

For instance, the latest 8 TeV limits using boosted techniques to search for $\mathrm{t\bar{t}}$ resonances of Kaluza-Klein gluons from Ref. [27] are shown in Fig. 2 and finally probe, for the first time, a viable region of parameter space available for models of ED that are not already disfavored by precision measurements [35]. Without the boosted-jet strategies for searches that Prof. Rappoccio has developed, it would not have been possible to access this regime at CMS by any other method. This highlights the absolutely critical nature of developing these tools in searches.

In addition to pioneering the searches for new physics using boosted-jet techniques, Prof. Rappoccio has also been instrumental in developing, commissioning, and maintaining the general jet reconstruction and particle-flow algorithms at CMS. Some of the areas in which he has played a leading role are the development of the “charged hadron subtraction” algorithm at CMS, where charged PF candidates associated with pileup vertices were removed directly from jets, resulting in a 10-20% improvement in the jet energy resolution, as well as the development of the median-p_{T}-per-unit-area pileup correction for jets at CMS. He was also instrumental in getting the “anti-k_{T}” algorithm [36] accepted by the CMS collaboration, and redesigned the software framework to make usage of the `fastjet` package [37, 38] so as to have a common algorithmic basis for jet reconstruction in ATLAS, CMS, and the theoretical community. He also participated in the software validation and data-quality monitoring (DQM) of the jets at CMS before and during the Run 1 startup commissioning at 2.36 and 7 TeV.

Furthermore, Prof. Rappoccio’s group has participated in the larger UB activities of FPIX commissioning and testing during the first year of his position. Dr. Dolen and Dr. Kumar developed tests for the FPIX high-density interconnect (HDI) modules using a probe station at Fermilab, leading a team of graduate and undergraduate students after severe budgetary constraints at Fermilab significantly reduced the number of people working on this particular part of the project.

Another past responsibility of Prof. Rappoccio at CMS was the Level-2 management position of the “Analysis Tools” subgroup of the Offline Project. During his tenure, Run 1 of the LHC began, and Rappoccio was responsible for guiding a team of people to ensure that proper analysis of the collision data could be done. This included such activities as minimizing the size of the “Analysis Object Dataset” (AOD) data tier, the primary access point for all CMS analyses, the development of the “Physics Analysis Toolkit” [39], and development and maintenance of the `FWLite` software framework, which is a small library of the CMS software tools (`CMSSW`) designed for usage by analysts.

Finally, Prof. Rappoccio has been involved in the review of 11 separate analyses at CMS as a member of the “Analysis Review Committee” (ARC).

2.3 Non-CMS Activities

To highlight the importance of the proposed research, the "SnowMass on the Mississippi" Community Summer Study [40] effort has made the identification of boosted jets an extremely high priority for the future of HEP in general. Dr. Dolen has been extensively involved in this effort, and is co-leading the group that focuses on boosted top-quark tagging techniques. The Snowmass "white paper" describing the need for these techniques, and the capability of future detectors to utilize them, is described in Ref. [41].

In addition, Prof. Rappoccio has played an integral part of the **BOOST** conference series and other conferences, such as the **Boston Jet Substructure Workshop**. The BOOST conference is the foremost conference on jet substructure and boosted-jet algorithms, and the conference reports in 2010 and 2011 are used as standard references in benchmarking these techniques [23, 24].

As a graduate student at Harvard University, Rappoccio also performed major updates and modifications of the Silicon Readout Controller (SRC) for the CDF experiment at Fermilab. These developments allowed the readout of the silicon detector at Level 1 of the CDF triggering system, which then could be passed to a tracking algorithm at Level 2. This made the extensive *B*-physics program at CDF possible, since without these track triggers, the quality of results would have been severely degraded.

Finally, for his expertise in the field of jet substructure, Rappoccio was the primary reviewer for the ATLAS paper describing jet substructure and boosted techniques in Ref [42], submitted to the *Journal of High Energy Physics* (JHEP).

3 Proposed Program of Research

The proposed program of research outlined here will have three separate timelines. The first is to finish the analysis of the 8 TeV collision data from Run 1 of the LHC. The second is to ensure that the discovery capacity of CMS using boosted jets is maximized at the onset of the 13 TeV run of the LHC ("Run 2"). The third is to further develop the capabilities of CMS at all levels (from detectors to analysis of data) in long-term planning of the high-luminosity LHC (HL-LHC, or "Run 3").

The focal point of this proposal is to pursue searches for BSM physics with boosted objects, described in Sec. 3.1.1. In addition to BSM searches, it is also important to characterize the SM contributions in these samples, and a program of study is described in Sec. 3.1.2.

For these goals to be met throughout the three LHC runs, many technical challenges must be met. The development and deployment of the particle flow [43] algorithm is discussed in Sec. 3.2.2. The collection and monitoring of data collection are outlined in Sec. 3.2.3. Finally, longer-term detector upgrades to the forward pixel (FPIX) detector are discussed in Sec. 3.2.4.

3.1 Proposed Physics Analyses

3.1.1 BSM Searches with Boosted Jets

The major motivation of this research proposal is the discovery of BSM physics with boosted jets. This is an ambitious goal, but one that Prof. Rappoccio is extraordinarily well-equipped to handle.

Rappoccio's tenure as "Beyond Two Generations" (B2G) Physics Analysis Group Convener at CMS continues until the end of 2014. The goals during this initial stage of the proposed research are to finish the analyses of the 8 TeV CMS data searching for BSM physics, to prepare in earnest for the upcoming LHC Run 2, and to motivate longer-term upgrades for LHC Run 3 ("Phase 1" and "Phase 2" CMS detector upgrades).

The immediate goal is to finish the analysis of well-motivated signals in the B2G group. The most important of these include searches for $\mathrm{t\bar{t}}$ resonances and heavy-quark partners. These are two clear signatures of ED that can be observed at CMS. The research program of the B2G group, under Prof. Rappoccio's guidance, includes several seminal "legacy" papers on these topics, to offer a final word on the 8 TeV data at the LHC. In addition, several other signatures are being investigated, including long-lived top quarks, dark matter signatures involving top quarks, and baryon-number violation in top quark decays.

There are two major analyses that Prof. Rappoccio's group has especially focused on in the past, and will continue to focus on in the future. Prof. Rappoccio's group are leading analysts on the $\mathrm{t\bar{t}}$ BSM searches, including the latest submission of a search in this channel [27]. While the current limits on BSM production of $\mathrm{t\bar{t}}$ are stringent, further improvements are possible with the Run 1 data. The full suite of existing jet substructure tools that Prof. Rappoccio has developed over the years (as described in Sec. 2.2), along with new additional techniques involving the combination of jet substructure and bottom-quark jet tagging, are expected to yield significant improvements over expected sensitivities in the $\mathrm{t\bar{t}}$ resonance search, of up to 30%.

Additionally, Prof. Rappoccio's group will continue to contribute to searches for diboson resonances ($WW/WZ/ZZ$) in the CMS Exotica group. Many advanced jet reconstruction techniques have already been deployed in this channel, but the paper of the combination of all of the various channels has not yet been completed. The research proposed here will help to bring this sensitive analysis to fruition.

In addition to the completion of the analysis of the LHC Run 1 data, the preparations for the startup of the LHC for Run 2 must be run concurrently. There are a suite of technical challenges to address in order for this to be accomplished, described in detail below in Sec. 3.2.

3.1.2 SM Measurements with Boosted Jets

The searches performed during the first run of the LHC have not yielded signals of BSM physics. However, these data can still be used to perform measurements of SM particles.

In particular, the differential cross section for $\mathrm{t\bar{t}}$ production at CMS [44] is sensitive to the case where top quarks are produced with resolved decay products. However, this limits the sensitivity of the measurement to top quarks with low p_{T}. The boosted-top identification techniques outlined in Sec. 3.1.1 can also select a very pure sample of $t\bar{t}$ pairs produced via SM mechanisms, and hence can also provide an opportunity to measure $t\bar{t}$ production in the highly-boosted regime where the traditional techniques have no sensitivity.

The measurement of the $t\bar{t}$ cross section in this regime is very interesting for a number of reasons. Firstly, it provides a sensitive test of perturbative QCD predictions for the NNLO $t\bar{t}$ production cross section that is not tested elsewhere. In addition, it may provide additional constraints on parton distribution functions (PDFs) for high-x partons. Finally, since the production of $t\bar{t}$ pairs at this kinematic range is dominated by $q\bar{q}$ production, tests of the forward-backward asymmetry could be measured to compare to those measured at the Tevatron [45]. The existing LHC measurements focus on the central-forward charge asymmetry [46, 47] because they are performed at low top-quark p_T, and are not sensitive to the same physics quantity. Explorations of this regime could provide an interesting point of comparison and may elucidate the anomalously large forward-backward asymmetry observed at the Tevatron.

Prof. Rappoccio is already leading a large effort at CMS to measure the $t\bar{t}$ production cross section for $p_T^{top} > 400$ GeV. This effort grew out of a CMS educational program, the CMS Data Analysis School at Fermilab in January 2013. Under Rappoccio's direction, a team of three faculty, one postdoc, four graduate students and four undergraduate students from UB, Cornell, Siena College, and Johns Hopkins are producing a measurement of the $t\bar{t}$ production cross section, fully corrected for detector effects.

3.2 Technical Challenges

3.2.1 Boosted Jet Algorithms

The performance of the boosted-jet algorithms at CMS will be heavily affected by increasing pileup in Run 2 and beyond. For instance, Fig. 3 was made by Dr. Dolen in the context of Snowmass (as described above), and shows the jet mass of a boosted top-quark jet in three separate cases during Run 3: without pileup (solid histogram), with 140 pileup interactions (open green histogram), and with 140 pileup interactions after applying an advanced boosted jet "grooming" technique (the "jet trimming" technique [22], in the open magenta histogram). The naive implementation of the "Run 1"-style algorithm to a higher pileup regime fails miserably. The major innovation of combining strengths from different techniques, however, can rescue the performance quite handily, and restores the jet mass almost back to the case where there was no pileup at all.

This is one example of a problem that was already identified and fixed by using innovative techniques to resolve the existing problems. There are several other major limitations that are also under investigation which will also require a heavy amount of development to solve for Run 2 and beyond. For example, boosted-jet techniques start to break down at very high energies because the SM particles are sufficiently boosted that their decay products fall into one single calorimeter cell. This could be mitigated, for instance, with a more finely-tuned PF algorithm as described in the next section. Only through a robust and comprehensive development and deployment strategy will these challenges be met.

The work outlined in this proposal includes the development of new techniques in order to fully realize the capability of the CMS detector in discovering new physics with boosted jets in an environment that is increasingly difficult to analyze. The success of this approach will require major innovations and cutting-edge tools, as well as a broad view of the field at large. The previous experience of Prof. Rappoccio has provided the expertise needed to solve these extensive problems, and can ensure that timely and deployable strategies can be developed prior to the startup of Run 2 of the LHC.

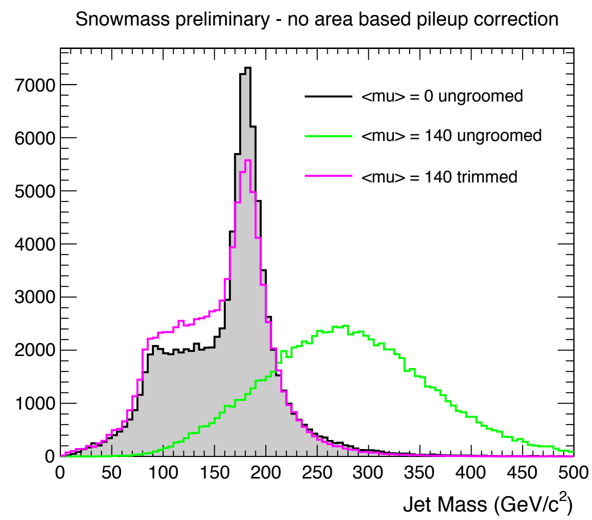

Figure 3: Jet mass for boosted top-quark jets produced at $\sqrt{s} = 8$ TeV. Three cases are shown : without pileup (solid histogram), with 140 pileup interactions (open green histogram), and with 140 pileup interactions after applying the jet trimming technique (open magenta histogram).

3.2.2 Particle Flow

The success of the general physics program at CMS during the first run of the LHC, and in particular of the jet substructure techniques outlined above, were heavily contingent on the PF algorithm [43]. When using the PF algorithm, performance of the top-tagging algorithms at CMS was increased by 20% compared to using calorimetric information only, driven by the superior energy and angular resolution of the algorithm. In addition, the PF algorithm is capable of removing over 60% of pileup directly, by removing charged hadrons that are associated to pileup vertices. This already reduces the scale of the problem of pileup considerably, and the substructure algorithms at CMS are heavily reliant on this technique.

The PF algorithm, however, is heavily tuned (by construction) on the Run 1 detector. A considerable amount of work must be done to migrate the PF algorithm to the new detector conditions, as well as to adapt to the enormous increase in pileup. In the coming "Phase 1" and "Phase 2" tracker and HCAL upgrades at CMS [48, 49] the detector will be improved in a number of ways, including the addition of a fourth silicon pixel layer to improve pileup rejection, and updates to the HCAL electronics to allow for readout of the longitudinal segmentation of hadronic showers. These upgrades will necessitate another tuning of the PF algorithm, with new opportunities and challenges directly ahead. Mr. Kaisen and Prof. Rappoccio are already working with the “global event description” (GED), tracking and HCAL groups at CMS to update the PF algorithm to take advantage of the new segmented HCAL readout, as well as the new pixel-detector configurations.

The success of the CMS boosted-object program is heavily contingent on the success of the PF algorithm. Without the superior energy and angular resolution of subjets and the pileup reduction capabilities of the PF algorithm, the substructure techniques we have developed will be significantly degraded.

However, with the newer detector comes new possibilities. It may be possible to mitigate the efficiency loss of jet substructure algorithms at very high energies (when the Lorentz boost is so large that all of the products decay in a single calorimeter cell) using the upgraded detector capabilities. For instance, combining information from the longitudinally-segmented readout of the HCAL with the finer angular segmentation of the ECAL and the trackers, it may be possible to lessen the impact of the intrinsic HCAL granularity. The upgraded CMS detector needs to be fully-utilized in order to maximize the potential for physics discoveries. Advanced development of the PF algorithm may illuminate new advantages that were previously impossible.

3.2.3 Trigger Development and Data Quality Monitoring

In order to analyze highly-boosted topologies in BSM searches, the relevant data must be collected in efficient triggers. Furthermore, the reconstruction, calibration, and trigger efficiencies of these algorithms must be incorporated in the overall program of data-quality monitoring (DQM) at CMS. At the present time, there are very few triggers that are capable of collecting boosted-jet events in the upcoming Run 2, and those that do exist necessitate very high kinematic thresholds which limit their sensitivity. This needs immediate rectification if we are to be prepared to adequately perform these searches for new physics with boosted objects detailed in this proposal.

A major difficulty here is that the jets in events in Run 2 will be highly-polluted with pileup interactions. In fact, using algorithms that we have previously developed in Run 1 to deal with pileup mitigation may not continue to work in Runs 2 and 3 with such large pileup. Since there is a large stochastic fluctuation of the pileup background (roughly 1 GeV per jet), with 140 pileup interactions, a 400 GeV jet will be expected to be composed of nearly 50% pileup.

Rigorous and expansive application of boosted-jet, jet-substructure, pileup removal, and other advanced techniques will be necessary to collect the boosted-jet datasets with reasonable efficiency without having enormously high event rates. For instance, if one were to select events with a jet-mass requirement, without any corrections the trigger rate would grow linearly with the number of pileup interactions, and without any corrections the trigger would rapidly become untenable. However, from the studies by Prof. Rappoccio in Ref. [30], it is observed that applications of grooming techniques to the jets can eliminate the growth of the jet mass with increasing pileup entirely. Further investigations in this avenue of inquiry are sure to yield extremely promising results.

Dr. Dolen and Ms. Alyari will partake in the analysis and development of the triggering program at CMS to ensure that boosted-jet searches will acquire the necessary data in Run 2 without having event rates that simply scale linearly with pileup. Furthermore, Ms. Alyari will be participating in the DQM of generic and boosted jets to ensure that the algorithms are being implemented effectively and that no adverse interactions occur unexpectedly, thereby ensuring the safety of the physics program proposed here.

3.2.4 Forward Pixel Detector Commissioning and Operations

In order to maintain the ability of the PF algorithm to perform pileup rejection in the foreseen high-luminosity run of the LHC (HL-LHC), good vertexing capabilities of the CMS detector are of the utmost importance. In addition to providing secondary-vertex identification in heavy-flavor jets, the upgraded pixel detector at CMS provides better efficiency for pileup track rejection, which is relied upon heavily in the aforementioned physics program. The planned "Phase 1" upgrade of the forward pixel (FPIX) detector at CMS is expected to add an additional pixel layer to improve fake track rejection, as well as to move the innermost pixel layer closer to the beam to provide a more sensitive impact parameter measurement.

Rappoccio's group, as well as the larger UB group and others in the US CMS program, are very active in the forward pixel (FPIX) detector commissioning for the Phase-1 upgrade. The UB group is involved with the US CMS NSF Cooperative Agreement "U.S. CMS Phase-1 Upgrades", Fastlane number 7334626, to support undergraduate students working on the CMS Phase 1 FPIX upgrade project. However, this Cooperative Agreement does not provide support for the graduate students nor postdoctoral fellows already working on the project.

In the past year, Rappoccio's group has begun working on the FPIX upgrade project. Dr. Dolen is permanently stationed at Fermilab to take advantage of the Silicon Detector (SiDet) Facility, and is already participating in the FPIX module testing. During the summer of 2013, the UB team (led by Dr. Dolen and Dr. Kumar) commissioned 50 High-Density Interconnect (HDI) boards for the FPIX modules, including visual inspection, spot checks of the connectivity of anomalies found by this visual inspection, and also randomized spot checks of interconnections to ensure high quality of the produced modules. For this exercise, a probe station was revived for usage at SiDet, and a LabView program was developed to do the testing.

In addition to the already completed activities, Rappoccio's group has committed to other HDI burn-in tests, tests of the half-disk assembly of the FPIX detector, beam tests (the first scheduled in Fall 2013), and overall commissioning of the FPIX detector. Longer-term activities will include operations and support of the upgraded Phase-1 pixel detector once it is installed at CMS.

4 Outreach and education

While it is critical to pursue a rigorous research program, a large part of the responsibility of scientists is to educate the next generation effectively. There is already extensive work being done to educate high school-level students and teachers via the *QuarkNet* program at UB, however there is very little in the way of educating the general public. In addition to participating in the existing *QuarkNet* activities, the plan outlined in this proposal will extend the coverage of the outreach program at UB to engage the broader public in discussions of major results in particle physics, as well as to enliven particle physics for young students. This will be implemented based on similar events as the "HiggsFest" [50] that Prof. Rappoccio organized at UB.

4.1 Higgsfest and other public events

The "Higgsfest" that was organized here at UB in 2012 is highlighted in Ref. [50]. The aim of the event was to invite the general public for "plain English" summaries and hands-on demonstrations that were geared for a multitude of age and knowledge levels. This was attended by over 100 people, including children, high-school students, physics and non-physics undergraduates, and interested members of the community.

Some of the hands-on demonstrations included building models of Feynman diagrams from craft material (for young children), a fully-functional four-layer coincidental muon scintillator detector, a cloud chamber made out of tupperware, felt, and dry ice, and the actual Higgs events from the CMS collaboration in an interactive event display. The event was covered by the "UB Reporter" here at UB [51].

Two more such events are proposed, the first to coincide with the LHC turn-on sometime in 2015, and the second to coincide with the newest results from the LHC after data-taking commences. These are events that should generate high media coverage, and will be a good opportunity to capitalize on public interest in this field. Having regular events to discuss the LHC results is a very long-term goal, and the opportunity to develop them with the CAREER proposal will be very useful. In the event of a major new discovery at the LHC during Run 2, the public interest will be very high, so having the experience of what works and what does not work in such events is extremely valuable to maximize the public impact.

In addition, this removes the stigma associated with science and technology fields at an early age. When young children can attend an event with their parents and take something away from it, this shows them that science is an integral part of life, and nothing to be particularly nervous about pursuing. It may even convince younger people to pursue a scientific career.

One of the major points learned during the last "Higgsfest" is that it is often difficult to have economically-disadvantaged students attend the lectures because of a lack of transportation possibilities. This is something to rectify for future projects along these lines. Therefore, in addition to holding the event directly at the UB North Campus (which is difficult for inner-city Buffalo schools to reach), a duplicated event is also proposed closer to the inner city that is easier to attend, or possibly to visit these schools directly. Some possible locations are the UB South Campus, or at "Babeville" [52], where the UB Physics

Department routinely organizes the "Science and Art Cabaret" [53]. Both locations provide the infrastructure needed for the event, and access for disadvantaged schools and students in the inner city of Buffalo.

4.2 Undergraduate research

Having been an undergraduate researcher, Prof. Rappoccio knows the importance of making a positive impression on undergraduates who are interested in pursuing an academic career. He is currently advising two undergraduate students in his group, Brendan Smith and Jonathan Goodrum. Mr. Goodrum is participating in the "Collegiate Science and Technology Entry Program" (CSTEP) here at UB. This program focuses on disadvantaged or minority students who would otherwise have a difficult time pursuing STEM-related fields. Prof. Rappoccio is a strong believer in the principles and practice of this program, and intends to continue this work in the future. Currently, Mr. Goodrum is participating in a study to increase the processing speed of jet-clustering algorithms (critical for the jet substructure outlined above) by investigating possible parallelization of the algorithms for multicore, multithread, and possibly graphical processing unit usage.

In addition, Mr. Smith obtained a complete hands-on immersion at the Fermi National Accelerator Laboratory (FNAL) during the summer of 2013. There, he participated in testing of major electronics modules for the forward pixel (FPIX) upgrade at CMS. This kind of experience is invaluable in the field of young researchers, and it is also planned to continue supporting undergraduate students in such hands-on activities at CERN next year under the NSF Cooperative Agreement that is under review at the present time, discussed in the "Current and Pending Support" section below (Proposal Number 7334626). Mr. Smith is also currently completing an undergraduate honor's thesis under the direction of Prof. Rappoccio.

5 Prior Work in Education and Outreach

As Prof. Rappoccio wholeheartedly believes in the importance of outreach and educational activity, he has extensively participated in outreach activities throughout his career. Some examples are

- **Facilitator, CMS Data Analysis School, Fermilab, Batavia IL (Jan 2013, Jan 2011)** : facilitated the education of new CMS members through tutorials and hands-on exercises of real-life measurements.
- **"Higgsfest" public lecture, Buffalo NY (Dec 6 2012)**: as described above, the "Higgsfest" was a celebration of the discovery of the SM-like Higgs boson at the LHC focused on outreach to the community.
- **Science Cabaret public lecture, Buffalo NY (Oct 17 2012)**: lecture about the statistics behind the discovery of the Higgs boson aimed at conveying the information to a group of members of the artistic and public communities in Buffalo.

- **Fermilab UEC Trip to Washington, D.C. (Spring 2009, Spring 2011)** : advocacy trip to visit members of Congress to spread information related to particle physics.

- **Angels and Demons public lecture, Bethlehem Public Library, Delmar NY (May 15 2009)** : related to the release of the film "Angels and Demons," a large-scale public lecture series was organized by the Fermilab outreach department, and Prof. Rappoccio gave the lecture at a library outside of Albany, NY.

- **Chicago Section of the Society for Applied Spectroscopy, Elmhurst, IL (Jan 13 2009)** : lecture of the methodologies and results of collider physics to an engineering society in the Chicago Area.

- **Lecture, Bethlehem Central High School, Delmar NY (Dec 4 2008)** : lecture to high-school students from the high school I graduated from about particle physics and the LHC.

- **Duckon Science Fiction Convention, Naperville IL (Jun 14 2008)** : lecture about the "real" science of the LHC compared to science fiction.

- **Starter Kit for LHC Newcomers and Physics Analysis Toolkit Tutorials, Fermilab, Batavia IL, also CERN, Geneva CH (throughout 2008-2009)** : as part of his duties for the LHC support team at Fermilab, Prof. Rappoccio developed an education program for students, postdoctoral fellows, and faculty that were new to the CMS experiment with hands-on examples, simple walk-through tutorials, and in-person support. This eventually developed into full-fledged activities at CERN for the tutorials, as well as was the precursor for the hugely successful "CMS Data Analysis School," as much of the material was initially developed there.

- Prof. Rappoccio currently oversees the research and education of **Joshua Kaisen** and **Maral Alyari** as graduate students in his group. Mr. Kaisen is working on upgrading the particle-flow algorithm to work in the upgraded CMS detector. **Ms. Alyari** will be working on data-quality monitoring of the particle-flow and jet-reconstruction algorithms.

- Previously, at JHU, Prof. Rappoccio also oversaw the graduate studies of **Guofan Hu, Marc Osherson, Kevin Nash, and Yongjie Xin** who are working on searches for BSM physics using boosted jet algorithms. Dr. Hu graduated recently and moved to a position in finance, while Mr. Osherson, Mr. Nash, and Mr. Xin are continuing their studies, still partially under his supervision.

- Prior to the monitoring of the activities of **Brendan Smith** and **Jonathan Goodrum**, at JHU Prof. Rappoccio monitored the activities of two undergraduate students, **David Bjergaard** and **Prateek Bajaj**. Mr. Bjergaard is now at Duke University pursuing a Ph.D. in particle physics.

6 Summary

In summary, the program that has been proposed here is ambitious and high-profile, but one in which Prof. Rappoccio has a unique talent set to accomplish. This program will have an excellent chance of uncovering BSM physics during Run 2 of the LHC and beyond. The previous experience of Prof. Rappoccio with boosted-jet techniques will be absolutely critical to ensure that the techniques are as successful in Run 2 as they were in Run 1, amidst a sea of technical challenges.

In addition to this ground-breaking research, an addition to the extensive outreach at UB is proposed in events such as successors to "Higgsfest" in the Buffalo area (including lower-income places that have limited access to suburban venues).