Energy Frontier Research With ATLAS: Final Report

Faculty:	Steve Ahlen, Kevin Black, John Butler
Research Faculty:	Jim Shank, Saul Youssef
Engineering Physicists:	Andrew Inglis, Zhen Yan
Research Associates:	Lidia Dell'Asta, Louis Helary
Graduate Students:	Clare Bernard, Mike Kruskal, Alex Long, Kevin Sanders, Alex Sherman, Efe Yigitbasi
Undergraduate Students:	Jessica Allan, Josh Levin, Emma Rosenfeld

1 Introduction

Boston University has been involved in the ATLAS experiment at the CERN Large Hadron Collider (LHC) since the mid-1990s. The BU group has made significant contributions to ATLAS across a broad spectrum of activities. This Final Report covers our group's activities from 2013 to 2015 where we played major roles in the muon system hardware and operations, the Phase I detector upgrade, the muon trigger, ATLAS computing, and the physics analysis of ATLAS data.

2 Muon Spectrometer

2.1 Muon System Work at Point 1

The BU group continues our longtime commitment to maintaining, improving, and operating the ATLAS muon system. The BU efforts are led by Zhen Yan with major contributions from Louis Helary. Yan is supported by US ATLAS M&O funding and supervised by Butler. Activities during the current grant period are briefly listed in the next sections. We plan to continue our pivotal role during Run 2 in the small team responsible for MDT M&O.

2.1.1 MDT Maintenance Work During LHC Long Shutdown 1

A partial list of BU work in the ATLAS Control Room (ACR) and cavern during LS1 follows:

- Yan was the Muon Run Coordinator until September 2013.
- Fixed all MDT problems in the cavern. This included recovering bad channels/tubes due to broken front-end electronics (> 200 tubes), high voltage problems (> 100 tubes), and low voltage problems (> 300 tubes).
- Performed MDT gas leak measurements for more than 4000 valves.
- Upgraded the MDT front-end firmware for more than 1000 chambers.
- MDT Small Wheel service disconnection/reconnection and readout recommissioning.

2.1.2 DCS Activities

A sample of the recent BU contributions to the muon slow controls system (DCS) follows:

- Developed the new Muon Rack Display Panel used by shifters in the ACR since September 2014.
- Developed the new Muon Status Overview Panel used by shifters in the ACR since May 2015.
- Yan performed a clever analysis of DCS data to uncover nascent low voltage problems affecting about 30 chambers before they became serious.

2.2 Shift Work

Our group maintains a strong commitment to running the experiment. We take more shifts than our quota and volunteer for on-call expert shifts. We have taken Shift Leader, Run Control and Muon subsystem shifts in Run 1 and will continue in those capacities for Run 2. We also currently serve as "MDT Primary" (Yan and Helary) and "Bphysics/Muons signatures" (Lidia Dell'Asta) on-call experts who are available 24/7 and critical for keeping a high operational efficiency for good quality data taking. Our students are expected to take ACR shifts during the time they are stationed at CERN.

2.3 Mezzanine Card Tester

The mezzanine, or "mezz", card is a key component of the MDT front-end electronics. About 15,000 mezz cards are currently installed in ATLAS. Another 400 mezz cards are presently being fabricated for use as spares and also for a small number of new MDT chambers intended to fill holes in the MDT acceptance. Unfortunately the original mezz-card test setup is no longer functional so there was a need for new tester hardware. We agreed with ATLAS muon system management to take on the task. The project was led by Eric Hazen from the BU electronics shop and Butler.
The new "all-in-one" mezzanine test board has been completed, see Fig. 1. This board includes a complete interface to the mezz card, including JTAG control, power supply with over-current sense, programmable pulse injection, and TDC readout. A SQLite database and root-based software have been developed to analyze and archive the test results. An example of the threshold offset test is shown in Fig. 1.
The testing on an initial batch of 50 mezz cards was done by undergraduate Jessica Allan and Butler. We used the results to tweak the input termination and fine-tune the test criteria that define "pass" and "fail". In the coming months the full complement of mezz cards will be validated for use in ATLAS. We built an additional four mezzanine tester setups; these will be commissioned and distributed to CERN and other ATLAS institutions.

3 Activities in Support of the Phase I Upgrade

Steve Ahlen directed efforts to develop quality control procedures for the micromegas detectors for the New Small Wheel (NSW), and to build a four-layer prototype for electronics testing at Harvard. The work was done by Ahlen and Mike Kruskal, Andrew Inglis and Emma Rosenfeld. Inglis and Rosenfeld were supported by NSF ATLAS project funds. Chamber construction was completed in 2014 and the chambers were shipped to Harvard for evaluation. This completes the BU participation in the Phase I Upgrade.

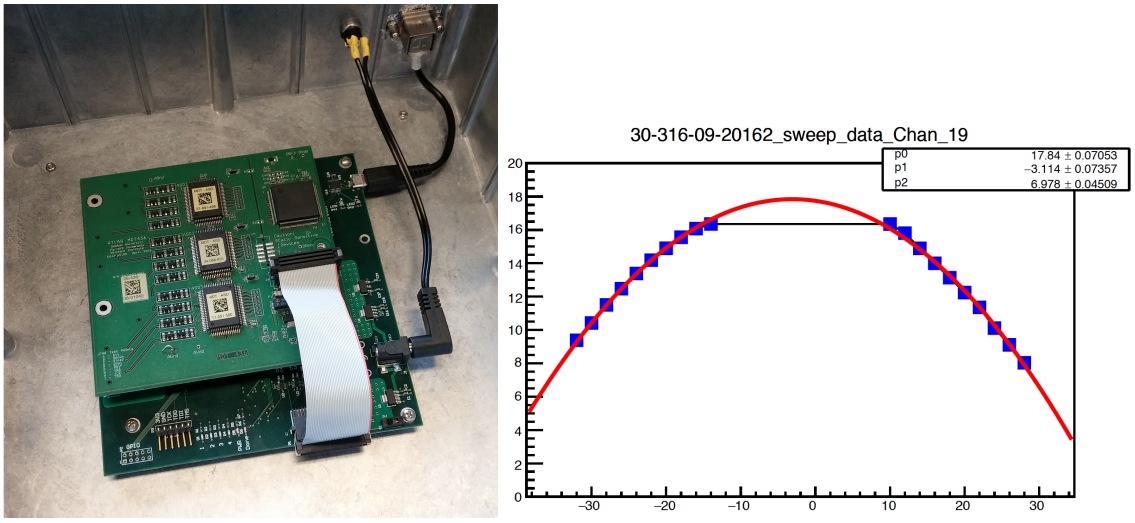


Figure 1: (left) The new "all-in-one" mezzanine test board is shown with a mezz card mounted in the test position. (right) An example of the noise rate vs. threshold scan used to determine each channel's threshold offset is within specification.

4 Muon Trigger

The BU group has made major contributions to the Muon High Level Trigger (HLT). Kevin Black was the convener of the ATLAS Muon Trigger Signature group ($\approx$ 30 scientists and students) which is responsible for the development of HLT algorithms and menu and measuring trigger performance between 2012-2015. Recently, Lidia Dell'Asta has become the group convener.

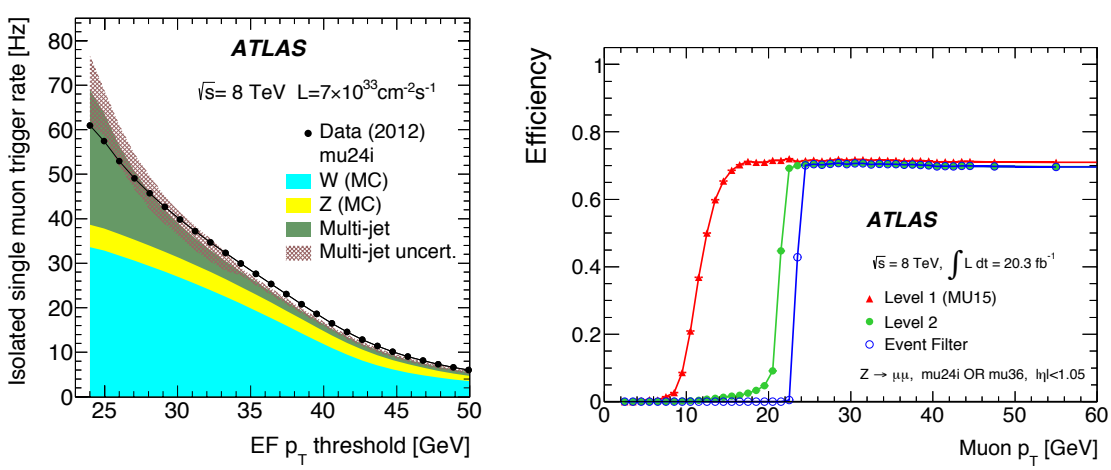


Figure 2: Trigger rate and sample composition as a function of HLT threshold (right) and single muon trigger turn-on (left).

Black oversaw the comprehensive overhaul of the Level 2 muon trigger algorithm to incorporate the most accurate geometry, calibration, and alignment information. This was a complete rewrite of a major and crucial component of the ATLAS trigger. This work was done by Black and graduate student Clare Bernard. Not only did this allow us to streamline the use of the offline tools for easier maintenance of the code it also allowed us to use more advanced particle tracking techniques leading

to improved performance and better physics results. Additionally, this was crucial for preparing for upgrades of the detector as it allows us to design and implement triggers tightly coupled to the planned hardware upgrade of the detector. During this time, Black was also responsible for the development of the menu of several hundred muon trigger selections that were implemented for use in Run 1. The menu was developed to trigger on events with vastly different event topology and event kinematics to broadly serve the physics goals of the ATLAS experiment. The performance of the muon trigger in Run 1 was documented in a recently published paper [1]. Black lead and oversaw the analysis and was the editor of the paper. Alex Long contributed many studies to the paper as part of his authorship qualification. Examples of the measured rate and performance of the lowest unprescaled single muon trigger are shown in Fig. 2.

From 2014 onward Dell'Asta was put in charge of the muon trigger menu development. This included building the "trigger chains" (the sequence of algorithms and hypotheses) that define the various trigger items for single muon, multimuon, and cross-item triggers as well as completing rate estimates for several hundred HLT menu items. The group also played a critical role in measuring the performance of the trigger, debugging the HLT software, and was responsible for the overall performance of the muon HLT for the previous four years. This includes, but is not limited to, maintaining the software package that reweights Monte Carlo events, masking out areas of the simulation that are not operational in data, and studying the detailed efficiencies, resolutions, and turn on of the muon trigger. These were both critical elements at achieving good data and simulation agreement in Run 1 as well as very important for the first ATLAS data at 13 TeV.

Our group will continue to play an important role in the development of new algorithms and triggers as well as performance and operations of the muon trigger in Run 2. In particular, we are are planning to work on an important component of the software upgrade for the trigger.

- For Run 2 there were several major improvements including the merging of the Level 2 and Event Filter computing farm into a common HLT. Additionally, the ATLAS experiment is commissioning a hardware based system that will process data on every Level 1 accept and track particles in the Inner Detector (ID). Although the tracks will only be available for the HLT, it represents a major branch point in the algorithm. In Run 1, tracking was only enabled at the software level around small regions of interest (ROI) defined by the Level 1 calorimeter and muon triggers. In Run 2, the ATLAS experiment is introducing a hardware based system that will provide tracks at the start of the HLT processing called the fast tracker FTK. We will work on the integration of the muon trigger with ID tracking. This consists of not only implementing, debugging, and optimizing the combination stage but also allows for many potential optimizations. The new FTK tracks will provide tracks for all regions of the detector with tracks $p_T > 1$ GeV. This allows the possibility of an "inside-out" algorithm, improved isolation calculations, and additional vertex constraints. Black will supervise Kevin Sanders in the integration of this new element of the trigger.

- Currently the muon trigger simulation is integrated into the GEANT simulation of ATLAS. This is a critical component of correctly estimating trigger efficiencies and biases in the Monte Carlo based simulations. However, it has also become a bottleneck since we have no fast emulation of the trigger. Thus, large samples must be produced, simulated, and often times re-simulated in order to get reliable trigger estimates. We will work on developing an emulation of the trigger system which will be capable of giving correct estimates of rates and efficiencies without needing to large fully simulated samples. Alex Sherman and Dell'Asta will develop this tool in the next year and it will become a institutional responsibility supervised by Black.

- The offline isolation tools group have developed many interesting and sophisticated tools to optimize the isolated lepton calculations and requirements. We will work to integrate these into the HLT to get better performance including the important case of "mini-isolation" which has been utilized to great success in the search for highly boosted objects. Butler will supervise Efe Yigitbasi in this work over the next year.

Additionally, the trigger menu development, rate estimation, and performance on Run 2 data will continue to be a BU institutional responsibility in Run 2.

5 The US ATLAS Northeast Tier 2 Center

One of the main contributions that BU makes to ATLAS is hosting and operating one of the five Tier 2 centers located in the US: the NSF funded Northeast Tier 2 Center (NET2). Computing at the US ATLAS Tier 1 and Tier 2 centers is dominantly grid computing using the OSG grid infrastructure and ATLAS-developed software such as PanDA (production and analysis) Rucio (data distribution) and xrootd/fax (data federation). As is true throughout the year, NET2, and the US Tier 1 and Tier 2s in general, make some of the largest contributions to global ATLAS computing both in production and analysis. For example, in calendar year 2014 through November 2014, we have run 2.5 million production jobs and 4.1 million analysis jobs for approximately 1000 analysis users consuming 811,000 wall-days in total. The main challenge of the work is to provide reliable and efficient computing resources while simultaneously adopting and helping to develop the ever-changing ATLAS and grid computing environments while, at the same time, also meeting and ambitious program of computing, storage and networking expansion to meet the needs anticipated for Run 2 of the experiment. In particular, in the past year, all of the major software systems (including PanDA, Rucio, FTS and xrootd) underwent major changes and had to be carefully re-integrated into our running infrastructure while minimally disturbing on-going physics analysis. Saul Youssef, supported by NSF funding, is the primary senior investigator responsible for the overall operation of NET2. Black is responsible for grant administration, ensuring that the Tier 2 and Tier 3 are up to date for physics analysis and data processing, and is contact person with the US ATLAS computing managers. NET2 has maintained a highly reliable site available to the collaboration 24/7 throughout the years in addition to running approximately 250k opportunistic jobs consumed by the Open Science Grid.

6 Physics Analysis

The BU ATLAS group has been actively involved in the analysis of ATLAS data from Run 1 and Run 2 and publication of the results. Table 1 summarizes these efforts. We are also active in presenting ATLAS results at conferences. A summary of our recent talks is shown in Table 2. Details of our analyses are given in the following sections.

6.1 Measurement of Top Quark Production Kinematics

Top-quark measurements have entered a high-precision era at the LHC where the cross sections for single top-quark and top-quark pair ($t\bar{t}$) production at a center-of-mass energy $\sqrt{s} = 7$ TeV are factors of 40 and 20 higher, respectively, than at the Tevatron. The large number of $t\bar{t}$ events makes it possible to measure precisely the $t\bar{t}$ production cross-sections differentially, providing precision tests of the current predictions based on perturbative Quantum Chromodynamics (QCD). The top

Reference	Topic	Role	Names
	Papers		
PRD 88 (2013) 072001	DBL - TeV gravity same-sign dimuon	Editorial Board	Black
PLB (2014) 223	DBL - Diboson lvll resonance 8 TeV	Analysis/Editor	Butler
		Analysis/Editor	Long
PLB 738 (2014) 428	DBL - Diboson Vgamma resonance 8 TeV	Analysis/Editor	Helary
JHEP 09 (2014) 037	LPX - Search for W' to lv at 8 TeV	Analysis/Contact Editor	Butler
		Analysis/Contact Editor	Long
JHEP 11 (2014) 104	HQT - VLQ to Zt/b + X at 8 TeV	Analysis/Editor	Black
EXOT-2014-18	DBL - diboson combination	Analysis/Editor	Butler
		Analysis/Editor	Long
EXOT-2014-20	JDM - monoH to bb	Analysis/Editor	Kruskal
JHEP 04 (2015) 117	HSG4 Main coupling H to tautau	Analysis/Editor	Black
		Analysis/Contact Editor	Dell'Asta
		Analysis/Editor	Helary
arXiv:1508.03372 [hep-ex]	HSG4 Lepton Flavour Violation	Editorial Board	Black
arXiv:1506.05623 [hep-ex]	HSG4 and TauCP Embedding	Analysis/Editor	Helary
PRL 112, 231806 (2014)	Z to 4 leptons xs 7 and 8 TeV	Editorial Board	Black
STDM-2014-09	inclusive prompt photons at 8 TeV	Editorial Board	Dell'Asta
STDM-2014-15	Inclusive 4l Lineshape	Editorial Board	Black
STDM-2015-07	WWW production with 2012 data	Analysis/Contact Editor	Helary
		Analysis/Editor	Butler
		Analysis/Editor	Long
PRD 90 (2104) 072004	Differential resolved cross section 7 TeV	Analysis/Contact Editor	Black
			Bernard
EPJ C (2015) 75	2012 muon trigger performance	Analysis/Contact Editor	Black
		Analysis/Editor	Long
	Publication Notes		
PUB-STDM-2015-05	W and Z at 13 TeV	Analysis/Editor	Black
		Analysis/Editor	Butler
		Analysis/Editor	Dell'Asta
		Analysis/Editor	Helary
	Conference Notes		
ATLAS-CONF-2013-055	Z to 4 leptons xs 7 and 8 TeV	Editorial Board	Black
ATLAS-CONF-2013-099	XS differential resolved cross section 7 TeV	Analysis/Contact Editor	Black
ATLAS-CONF-2013-108	HSG4 Winter 2013 tautau SM Higgs	Analysis/Editor	Black
		Analysis/Contact Editor	Dell'Asta
		Analysis/Contact Editor	Helary
		Analysis/Editor	Kruskal
ATLAS-CONF-2014-017	LPX - Search for W' to lv at 8 TeV	Analysis/Contact Editor	Butler
ATLAS-CONF-2014-061	HSG4 Main coupling H to tautau	Analysis/Editor	Black
		Analysis/Contact Editor	Dell'Asta
		Analysis/Editor	Helary
ATLAS-CONF-2015-045	DBL - diboson combination	Analysis/Editor	Butler
		Analysis/Editor	Long
ATLAS-CONF-2015-041	Z+jets at 13 TeV	Analysis/Editor	Black
		Analysis/Editor	Butler
		Analysis/Editor	Dell'Asta
		Analysis/Editor	Helary
ATLAS-CONF-2015-039	W and Z cross sections at 13 TeV	Analysis/Editor	Black
		Analysis/Editor	Butler
		Analysis/Editor	Dell'Asta
		Analysis/Editor	Helary

Table 1: Recent papers and conference notes with major BU ATLAS group contributions.

Title	Conference	Speaker
"The Upgraded ATLAS Trigger and Data Acquisition System"	DPF Ann Arbor 2015	Black
"Search For Vector Like Quarks with the ATLAS Detector"	"Wine & Cheese" FNAL 2015	Black
"Search For Vector Like Quarks"	Argonne 2014	Black
"Vector Like Quarks at an Upgraded LHC"	Snowmass: Energy Frontier Workshop, BNL, 2013	Black
"Muon Trigger Performance at ATLAS"	Lepton-Photon 2013	Black
"Exotic Physics Results at the LHC"	PIC Beijing 2013	Black
"Search for high-mass resonances and other exotica at the LHC"	Moriond EW 2013	Butler
"SM Higgs Physics"	US ATLAS Physics Workshop 2015	Dell'Asta
"Search for $H \to \tau\tau$ decays with a cut based analysis: status and prospects"	US ATLAS Physics Workshop 2014	Dell'Asta
"Search for the Higgs boson in fermionic channels using the ATLAS detector"	LLWI 2014	Dell'Asta
"The ATLAS Muon and Tau Trigger"	ACAT Beijing 2013	Dell'Asta
"A big orchestra for big discoveries"	TEDxWomen Milano 2013	Dell'Asta
"Wgamma/Zgamma production and NP constraints in ATLAS"	EPS-HEP 2013	Helary
"Differential top quark pair production measurements"	ICNFP Crete 2013	Bernard
"Online Muon Identification of the ATLAS Experiment"	ICATPP Como 2013	Bernard
"Searches for dark matter and extra dimensions with the ATLAS detector"	ICNFP 2014	Kruskal
"Search for $WWW \to l\nu l\nu l\nu$ production the ATLAS detector at $\sqrt{s} = 8$ TeV	APS 2015	Long

Table 2: Recent invited talks by the BU ATLAS group.

quark plays an important role in many theories of beyond Standard Model (bSM) physics and differential measurements have been proposed to be sensitive to new physics effects.
Black and Clare Bernard played a key role in the measurement of the $t\bar{t}$ differential cross-section as function of several kinematic variables. Kinematic reconstruction of the $t\bar{t}$ system was performed using a likelihood fit. The results were unfolded to the parton level after QCD radiation, and the normalized differential cross-section measurements were compared to the predictions of Monte Carlo (MC) generators and next-to-leading-order (NLO) QCD calculations. The p_T of the $t\bar{t}$ system system invariant mass, $m_{t\bar{t}}$, along with the top quark p_T and pseudo-rapidity (η) spectra were also compared to NLO QCD calculations including next-to-next-to-leading-logarithmic (NNLL) effects, examples are shown in Fig. 3.
Bernard and Black were responsible for the development and testing of the unfolding code, the multijet background estimation, and comparison of many topological and kinematic variables in control regions. Additionally, Black served as co-editor of the publication [2].

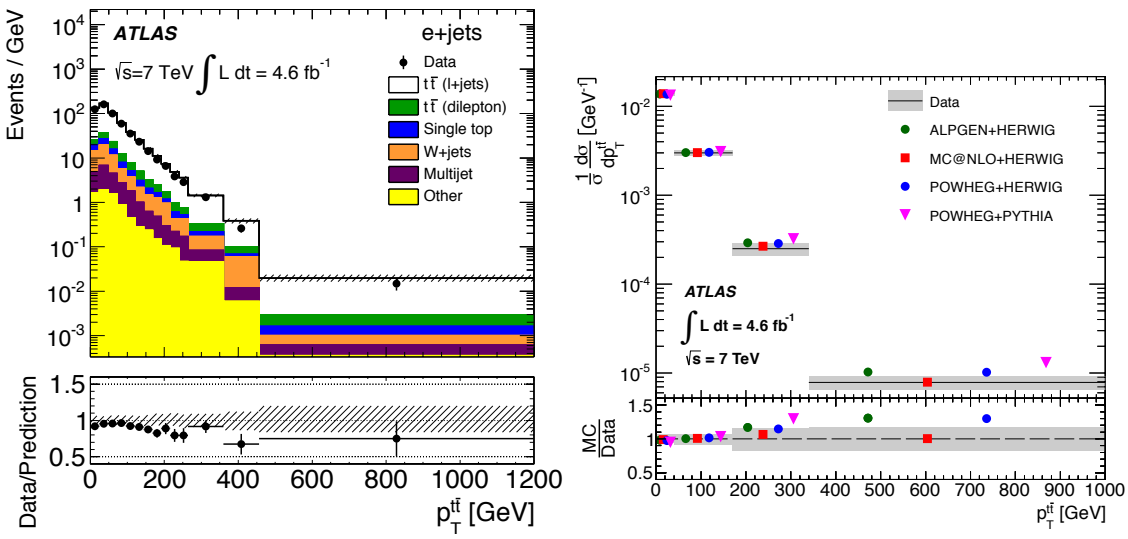


Figure 3: Transverse momentum spectra of the top quark pair system ($p_T^{t\bar{t}}$) with background estimation (left) and the normalized differential cross-section as a function of ($p_T^{t\bar{t}}$) (right).

The measurement provided a stringent test of perturbative QCD, contributed to patron-distribution function improvements, and provided critical input to top quark production modeling. The results were also used to reweigh top Monte Carlo production to obtain an much better agreement in many Higgs measurements as well as beyond the standard model searches.
For Run 2, we have begun to get involved in the measurement of the $t\bar{t}$ production cross-section. Black and Sherman will work on extending the previous work with Run 2 data by examining several new variables that have been suggested to have more sensitivity to physics beyond the standard model than the ones studied previously, including the angles between the top quarks in the lab frame, the "out of plane momentum" (the projection of one top quark's momentum out of the plane defined by the axis between the other top quark and the beam line), and the scattering angle between the two top quarks.

6.2 Search for WWW Production

The ATLAS collaboration has recently reported the first evidence for the production of a tri-boson final state. The precise study of these processes allows one to test the structure of the Standard Model electroweak sector. Butler, Helary and Long have been deeply involved in the search for the WWW final state, where the 3 W bosons decay into a lepton (e or μ) and a neutrino, and using 20 fb$^-$1 of pp collisions at a center-of-mass energy of 8 TeV.
Under the guidance of Butler, Helary is leading the ATLAS analysis group, while Long has been the main analyzer of the group who has in particular determined the background composition in this final state, performed the cut optimization to increase the signal sensitivity, and developed the statistical framework to interpret the data. This work is the subject of Long's PhD thesis.
The analysis has been recently un-blinded in the different signal regions and a very good agreement between the data and the prediction, including the signal, has been found as can be seen in Fig. 4 which shows the preliminary results for this analysis. Figure 4 (a) shows the lepton flavor multiplicity in the signal region containing three leptons and no same flavor opposite sign pairs; this is the region with the highest signal to background ratio. In this region the signal-plus-background model predicts 3.8 events with 5 events in data. Figure 4 (b) shows the contour of the profile-likelihood fit as a function of the fiducial cross-section obtained after combining all the signal regions. The measured value is extracted from the minimum of this curve, while the shape is used to obtain an uncertainty (at 68%) on the measurement. The fiducial cross-section measured by this analysis is: $\sigma(WWW \to \ell\nu\ell\nu\ell\nu) = 301 \pm 330(\text{stat}) \pm 330(\text{sys})$ ab.
The current focus of the group is on the combination of the results with another analysis group looking for the WWW final-state in the $\ell^{\pm}\nu\ell^{\pm}\nu jj$ channel, and to set limits on the production of anomalous quartic gauge couplings. These results will be released in an ATLAS article written by Helary and in Long's PhD thesis.

6.3 Evidence for the Decay Higgs $\to \tau\tau$

To establish the mass generation for fermions as implemented in the SM, it is of prime importance to demonstrate the direct coupling of the Higgs boson to fermions and its proportionality to mass. The most prominent candidate decay modes are the decays into tau leptons, $H \to \tau\tau$, and bottom quarks, $H \to b\bar{b}$.
After the discovery of the Higgs Boson, Black lead the BU group to get deeply involved and has played a fundamental role in the search for the decay of the Higgs boson into tau pairs. In first results published in November 2012, based on the full proton-proton collision dataset at a center of mass energy of 7 TeV and on the partial 8 TeV dataset, the cut-based analysis did not have enough sensitivity for an observation. Therefore a more complex analysis through multivariate techniques was tried. This work has brought to the observation of this decay in November 2013 with the analysis of the full dataset of proton-proton collisions at a center of mass energy of 8 TeV. The observed (expected) deviation from the background-only hypothesis corresponds to a significance of 4.1 (3.2) standard deviations, and the measured signal strength was $\mu = 1.4^{+0.5}_{-0.4}$. The final analysis of the full Run 1 ATLAS dataset, done on the proton-proton collisions in 2011 and 2012 at center of mass energies of 7 and 8 TeV respectively, has been recently published [3]. The main analysis was performed using multivariate techniques; a simplified and less sensitive cut-based analysis was also used as a cross check. With the Run 1 dataset, an excess of events over the expected background from other Standard Model processes is found with an observed (expected) significance of 4.5 (3.5) standard deviations, as shown in Fig. 5(a). This excess (Fig. 5(b)) provides evidence for the direct coupling of the Higgs boson to fermions. The measured signal strength, normalized to the

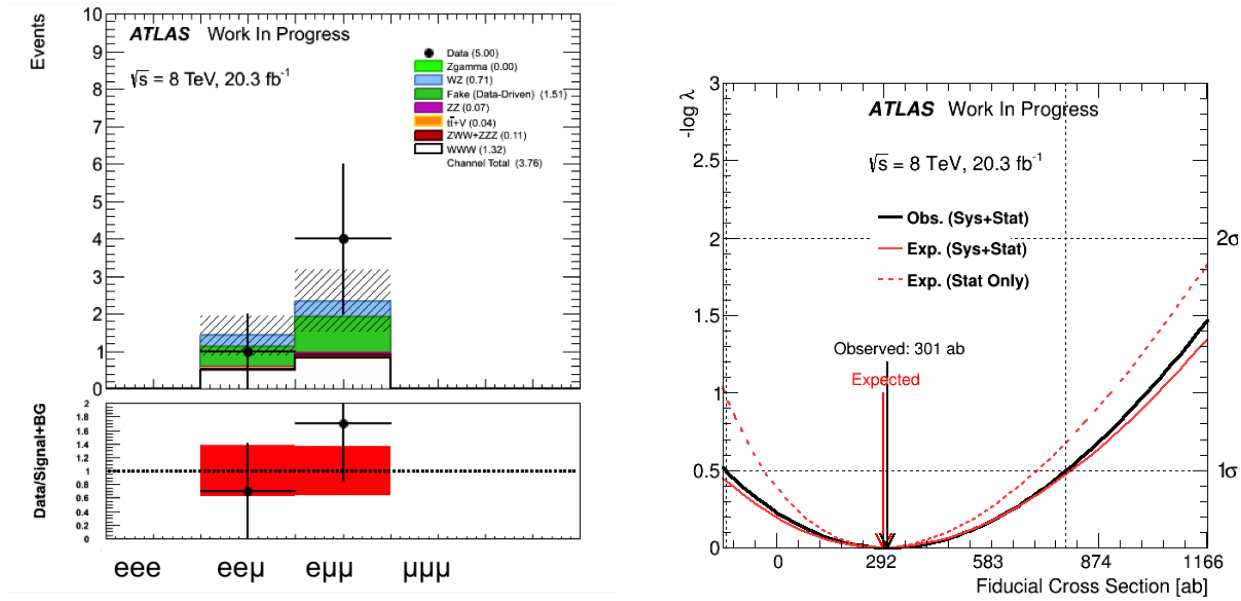


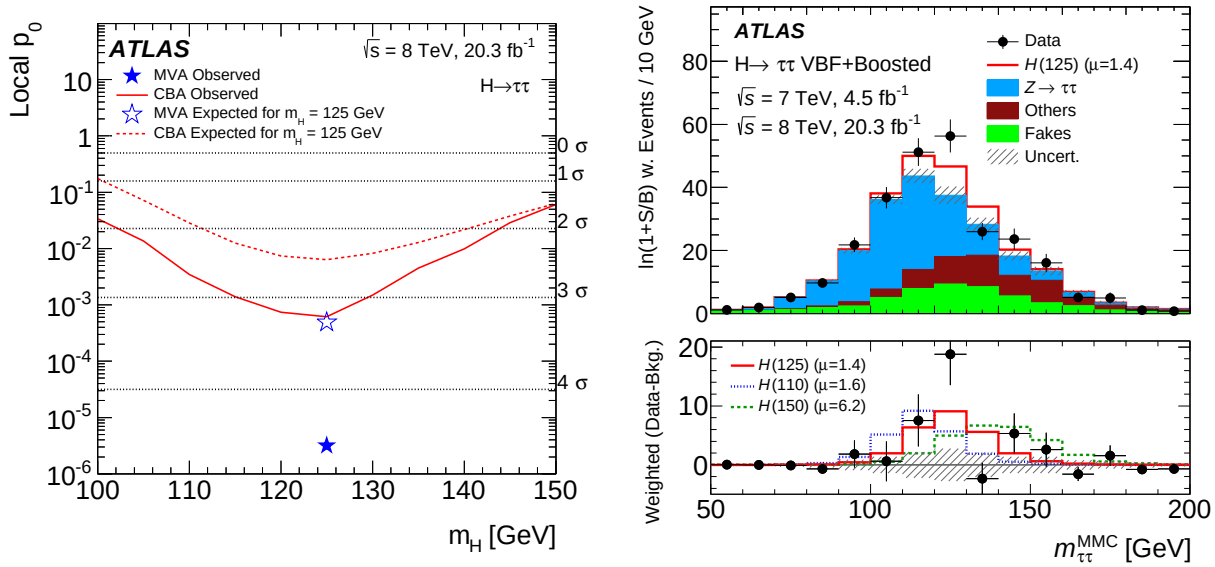
Figure 4: (a) Number of electrons and muons in the signal region containing no same flavor opposite sign pairs, (b) Profile likelihood contour as a function of the fiducial cross-section for the combination of all signal regions.

Standard Model expectation, of $\mu = 1.42^{+0.43}_{-0.37}$ is consistent with the predicted Yukawa coupling strength in the Standard Model. These results were included in the final Run 1 ATLAS paper on Higgs boson production and decay rates and coupling strengths recently submitted to EPJC. Combining all production modes and decay channels, the measured signal yield, normalized to the Standard Model expectation, is $1.18^{+0.15}_{-0.14}$.

The involvement of the BU group has focused on several aspects of the analysis which were overseen by Black. Dell'Asta has been the coordinator of the group working on the fully leptonic decay channel (where both taus decay leptonically) and has also been the main editor of the paper. Helary has been instrumental in the estimation of the $Z \to \tau\tau$ background, which is the main and largely irreducible background source. This background is not estimated from MC, but from data using the embedding technique. This technique consists first in the selection of $Z \to \mu\mu$ events from data. The muons are then removed and replaced by simulated taus. In this approach, essential features such as the modeling of the kinematics of the produced boson, the modeling of the hadronic activity of the event (jets and underlying event) as well as contributions from pile-up are taken from data. A detailed description of the embedding was recently submitted for publication [4], Helary served as an analyst and editor for the paper.

6.4 Search for New Heavy Gauge Bosons

Many BSM models predict new charged gauge bosons, generically called W's, that can be searched for in the lepton ($e^{\pm}$ or $\mu^{\pm}$) plus missing transverse energy (E_T^{miss}) final state. Alex Long and Butler have played major roles in the analysis of the 8 TeV data from 2012. Notable among his many contributions, Long performed very detailed studies to determine the higher-order QCD corrections (i.e. K-factors) and their uncertainties to the W' signal and the dominant charged-current Drell-



(a) (b)

Figure 5: (a) Observed (solid red) and expected (dashed red) p_0 values as a function of m_{H} in the cut-based analysis (CBA) for the data taken at $\sqrt{s} = 8$ TeV. The corresponding observed and expected p_0 values for the multivariate analysis (MVA) are indicated for $m_{\mathrm{H}} = 125$ GeV by a full and open star respectively. (b) Distributions of the invariant $\tau\tau$ mass, reconstructed using the missing mass calculator, $m_{\tau\tau}^{\mathrm{MMC}}$. The simulated $m_{\mathrm{H}} = 125$ GeV signal is plotted with a solid red line, the data is plotted with black dots.

Yan background cross-sections. Long also calculated the higher-order electroweak corrections for the background. An example of the QCD K-factor for W^+ production is shown in Fig. 6 (left) where the PDF uncertainty is illustrated.

No evidence for a W' signal was observed and limits were set. A W' with Sequential Standard Model couplings was excluded at the 95% confidence level for masses up to 3.24 TeV, see Fig. 6 (right). The analysis also set limits on excited chiral bosons (W^*) and dark matter pair production in association with a leptonically decaying W. Butler served as Analysis/Contact Editor for the publication [5] and was editor of the support note [6].

Long and Butler contributed to an internal effort to combine the results from the ATLAS W' and Z' [7] searches. The aim was to set limits more generically on couplings to new gauge bosons rather than only addressing a small set of specific models. We do not expect a Run 1 result from this work but the exercise was important in establishing the analysis methodology for Run 2.

6.5 Search for Vector-Like Quarks

The BU group played several important roles in the search for new physics including searches for heavy new quarks. Black was the exotics subgroup convener for the "Heavy Quark and Top" exotics subgroup for 2013-2014. This meant overseeing the work of approximately 40 scientists and students and shepherding approximately 15 different analysis to publication. Additionally the group played a primary role in the search for vector-like quarks in Run 1.

Proposed models of physics beyond the SM typically address the naturalness problem by postulating a new symmetry. For example, Supersymmetry is a Bose-Fermi symmetry, and the new states

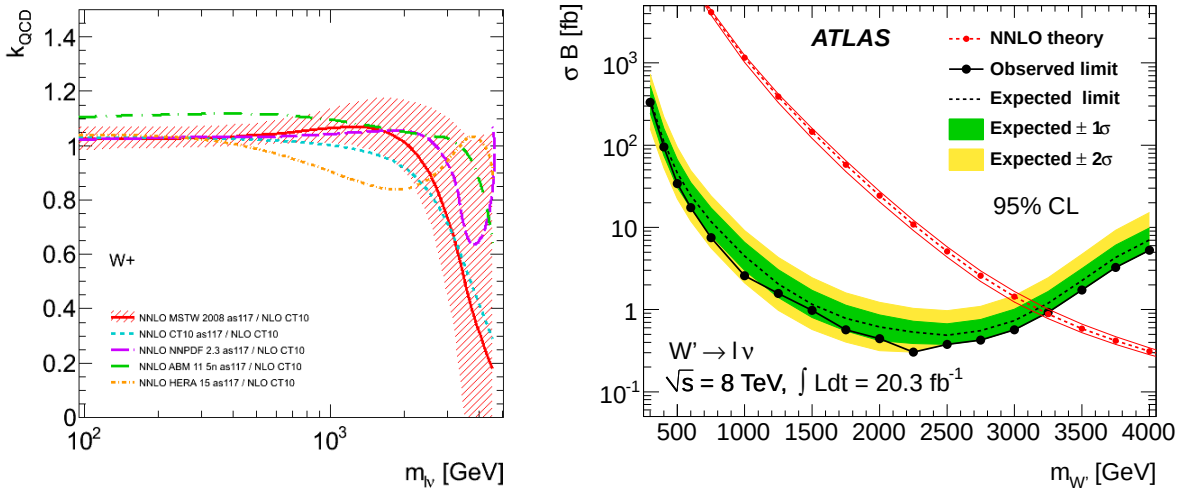


Figure 6: (Left) QCD K-factor as a function of W^+ mass, showing the uncertainty band for the nominal PDF, NNLO MSTW 2008, plus the central values for several other PDFs. (Right) The limit on σB for $W' \to \ell\nu$ production as a function of W' mass [5].

related to the SM bosons and fermions by this symmetry introduce new interactions that cancel the quadratically divergent ones. Alternatively, the symmetry could be a spontaneously broken global symmetry of the extended theory, with the Higgs boson emerging as a pseudo-Nambu-Goldstone boson. Examples of models that implement this idea are Little Higgs and Composite Higgs models. The new states realizing the enhanced symmetry are generically strongly coupled resonances of some new confining dynamics. These include vector-like quarks, defined as color-triplet spin-1/2 fermions whose left- and right-handed chiral components have the same transformation properties under the weak-isospin gauge group. Such quarks could mix with like-charge SM quarks , and the mixing of the SM top quark with a charge +2/3 vector-like quark could play a role in regulating the divergence of the Higgs mass-squared. Hence, vector-like quarks emerge as a characteristic feature of several non-Supersymmetric natural models.

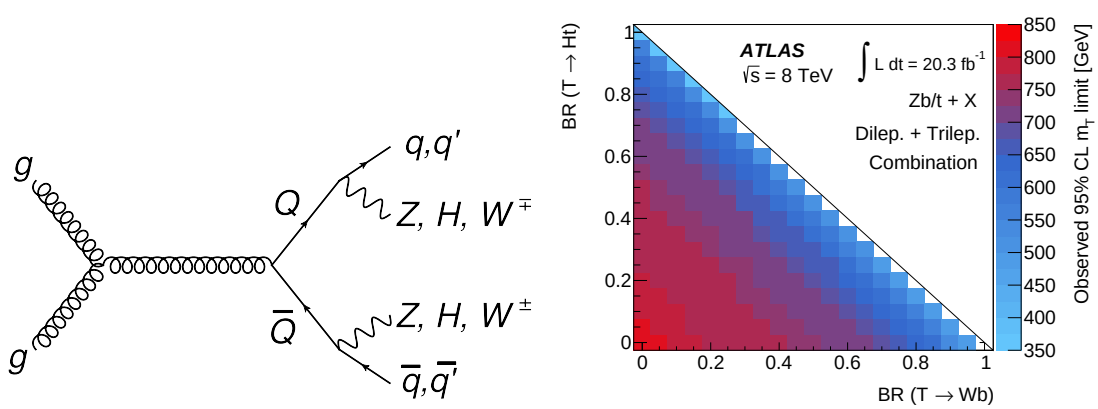


Figure 7: Feynman diagram for the pair production of VLQ at LO in QCD (left) and ATLAS limits from Run 1 from the "Z-tag" analysis (right).

Black and Bernard lead a search with ATLAS data collected in pp collisions at $\sqrt{s} = 8$ TeV for

the production of charge +2/3 (T) and -1/3 (B) vector-like quarks that decay to a Z boson and a third-generation quark (T $\rightarrow$ Zt and B $\rightarrow$ Zb). We selected events that contain a high transverse momentum Z boson candidate reconstructed from a pair of oppositely charged same flavor leptons and then were separated on the presence of an additional third high p_T lepton. This was the first LHC search to consider both QCD pair production and EW single production. We were responsible for the entirety of the trilepton search from background predictions, event selection optimization, and interpretation. The absence of any excess observed over data put some of the world's tightest constraint for VLQ in this decay scenario. Limits from this search were published in Ref. [8].
Black intends to extend these searches in the early Run 2 data. The near factor of two in the center-of-mass energy translates into a significant increase in the range of sensitivity for the hypothesized particles. Critically, the role of single production, boosted topologies, and more sophisticated analysis techniques are being developed by Black and Sherman. Black spent the summer of 2014 through the fall of 2015 as a US ATLAS scholar collaborating with Argonne National Laboratory scientists and has begun investigating these topics for Run 2 searches. These techniques will become of increasing importance for the large high energy data sets that are going to be collected in the next few years.

6.6 Dark Matter + Heavy Flavor Search

One of the most compelling questions in particle physics today is the nature of dark matter (DM). In some scenarios, pp collisions at the LHC can pair produce dark matter particles (χ and $\bar{\chi}$) in association with a b-quark or a pair of heavy quarks (b or t). The DM particles do not interact in the detector and are observed as missing transverse energy. Mike Kruskal searched for the DM+b final state, the analysis formed the basis of his dissertation under the supervision of Ahlen. Kruskal made a number of important contributions to the analysis, including using a jet smearing method to estimate the multi-jet background and a data-driven estimate of the dominant $Z \rightarrow \nu\bar{\nu}$ background. He was also involved in other aspects of the support note and paper, including systematic error calculations, validation of backgrounds, limit setting, and the theory behind the search.
The published results [9], interpreted in the framework of an effective field theory, were found to be consistent with the Standard Model. Exclusion limits were strongest at low DM masses. The limit on the cross-section mediated by the D1 operator was improved significantly with respect to previous ATLAS results, see Fig. 8. The sensitivity obtained for a spin independent cross section for nucleon-dark matter scattering was 10^{-42} cm^2 for $m_\chi = 10$ GeV. Constraints on dark matter models with enhanced couplings to b-quarks were also obtained. For $m_\chi = 35$ GeV, mediator particles with masses between 300 and 500 GeV were excluded, see Fig. 8.

6.7 The W and Z production cross section at 13 TeV

The large single electroweak boson production cross-section and clean leptonic decays of the W and Z bosons provide an ideal environment to study kinematics of W and Z production and decay with the first data collected from Run 2. The inclusive production of W and Z bosons is expected to increase by a factor of 1.7 in 13 TeV proton-proton collisions compared to 8 TeV. Furthermore, these studies are vital to validate the object reconstruction, detector calibration, and detector simulation. The initial analyses of the W and Z production cross-sections based on 85 pb^{-1} of 13 TeV data are already available [10] [11]. Representative results are shown in Fig. 9.
The BU group became involved in this early analysis as a way to contribute to one of the first Run 2 measurements and to begin to calibrate the detector and commission the Run 2 software. We played several key roles in the $W \rightarrow \mu\nu$ analysis. Black, Dell'Asta, Sherman and undergraduate

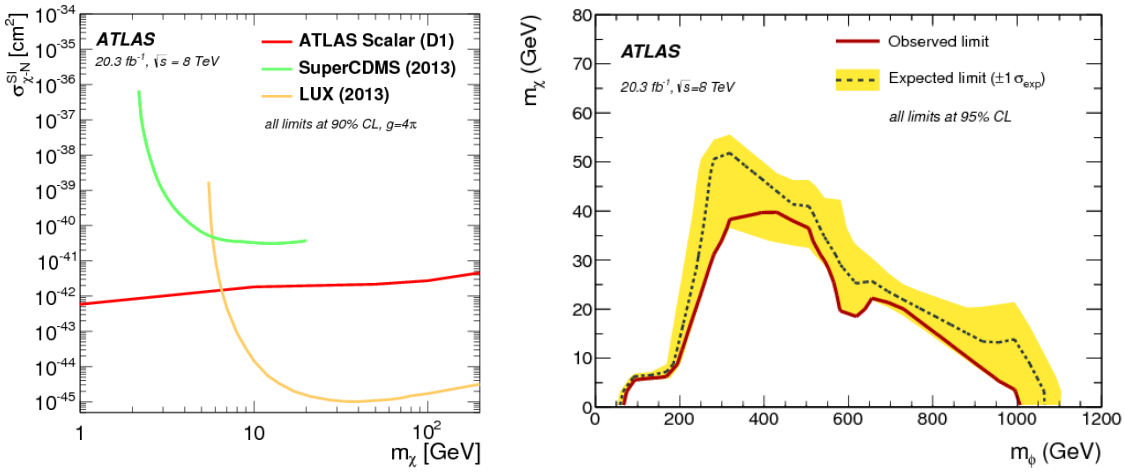


Figure 8: (left) Upper limits on the spin-independent $\chi-$nucleon cross-section, (right) Exclusion contour for the b-Flavoured Dark Matter model.

Joshua Levin studied the muon trigger efficiency in early 13 TeV data and implemented a package to correct the simulated events to the observed efficiencies in data. These scale factors were then integrated into the analysis. Yigitbasi, with help from Helary and Butler, performed detailed studies of the missing traverse energy definition and performance in data and simulation. This work will be included in the publication which is targeted for later this year.

7 BU Positions of Responsibility Within ATLAS

A summary of positions of responsibility held by BU group members during the period of our current 3-year grant follows:

- Kevin Black: Muon Trigger Signature convenor, Exotics *Heavy Quarks and Top* subgroup convener, ATLAS Analysis Model Framework Task Force, US ATLAS Speakers Committee (chair), US ATLAS Analysis Support Center Task Force
- John Butler: ATLAS Speakers Committee (elected), Exotics Data Production Coordinator, Exotics Physics Analysis Tools Liaison, ATLAS Group DPD contact, US ATLAS Tier-3 Task Force, US ATLAS Analysis Support Center Task Force, US ATLAS Management Advisory Committee (elected)
- Lidia Dell'Asta: Higgs to $\tau\tau$ leptonic final state subgroup organizer, Muon Trigger Signature convenor, Bphysics/Muons signatures on-call expert
- Louis Helary: Standard Model *Electroweak* subgroup convener, Standard Model group $E_{\mathrm{T}}^{\mathrm{miss}}$ contact, MDT primary on-call expert
- Jim Shank: Computing Advisor to US ATLAS Management
- Zhen Yan: Muon Run Coordinator, MDT primary on-call expert
- Saul Youssef: manager of Northeast Tier-2 center

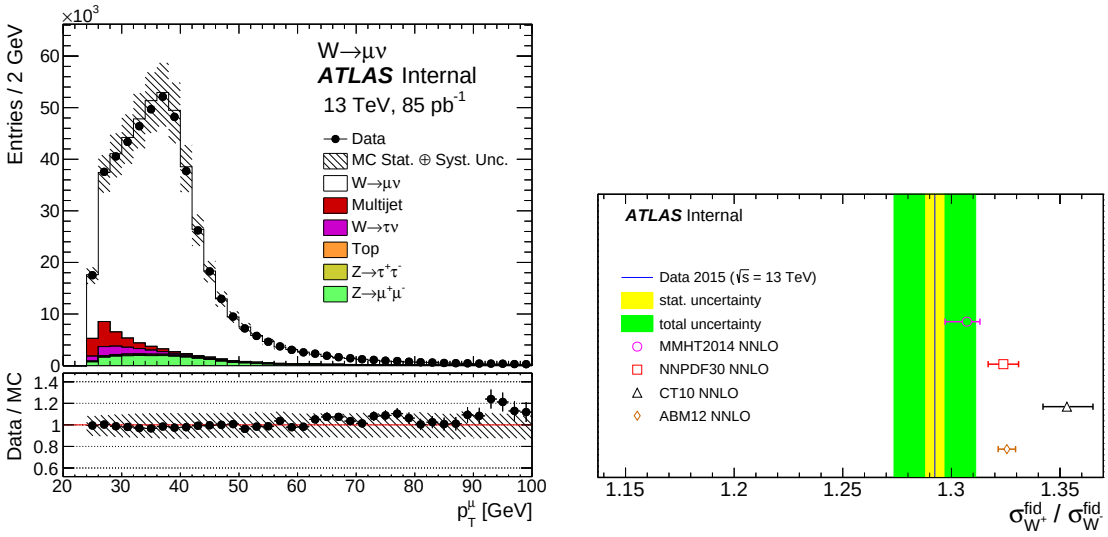


Figure 9: Transverse mass of $W \to \mu\nu$ candidates (left) and the ratio of W^+ to W^- cross-sections (right).

8 BU ATLAS Group Graduate Students

The following students received their PhD degrees during the 2013-2015 period: Clare Bernard, Mike Kruskal and Alex Long.

9 Publications

Members of the BU group are authors on all ATLAS papers published to date. A complete list of publications, over 500 and counting, can be found at `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Publications`.

References

[1] ATLAS Collaboration, *Performance of the ATLAS muon trigger in pp collisions at $\sqrt{s} = 8$ TeV*, Eur. Phys. J. **C75** (2015) no. 3, 120, `arXiv:1408.3179 [hep-ex]`.

[2] ATLAS Collaboration, *Measurements of normalized differential cross-sections for $t\bar{t}$ production in pp collisions at $\sqrt{s}$=7 TeV using the ATLAS detector*, Phys.Rev. **D90** (2014) 072004, `arXiv:1407.0371 [hep-ex]`.

[3] ATLAS Collaboration, *Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector*, JHEP **04** (2015) 117, `arXiv:1501.04943 [hep-ex]`.

[4] ATLAS Collaboration, *Modelling $Z \to \tau\tau$ processes in ATLAS with τ-embedded $Z \to \mu\mu$ data*, `arXiv:1506.05623 [hep-ex]`.

[5] ATLAS Collaboration, *Search for new particles in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP **1409** (2014) 037, `arXiv:1407.7494 [hep-ex]`.

[6] D. L. Adams et al., *Search for new heavy gauge bosons in the charged lepton plus missing transverse energy final state using pp collisions at $\sqrt{s}$ = 8 TeV in the ATLAS detector*, Tech. Rep. ATL-COM-PHYS-2012-1771, CERN, Geneva, Dec, 2012.

[7] ATLAS Collaboration, *Search for high-mass dilepton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Phys. Rev. D **90** (Sep, 2014) 052005. `http://link.aps.org/doi/10.1103/PhysRevD.90.052005`.

[8] ATLAS Collaboration, *Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, `arXiv:1409.5500 [hep-ex]`.

[9] ATLAS Collaboration, *Search for dark matter in events with heavy quarks and missing transverse momentum in pp collisions with the ATLAS detector*, Eur. Phys. J. **C75** (2015) no. 2, 92, `arXiv:1410.4031 [hep-ex]`.

[10] ATLAS Collaboration, *Measurement of W and Z Boson Production Cross Sections in pp Collisions at $\sqrt{s}$ = 13 TeV in the ATLAS Detector*, Tech. Rep. ATLAS-CONF-2015-039, CERN, Geneva, Aug, 2015. `https://cds.cern.ch/record/2045487`.

[11] ATLAS Collaboration, *Measurement of the Production Cross Sections of a Z Boson in Association with Jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, Tech. Rep. ATLAS-CONF-2015-041, CERN, Geneva, Aug, 2015. `https://cds.cern.ch/record/2048104`.