The Goals and Expected Scientific Impact of the US ATLAS Heavy Ion Program:

Input to the QCD White Paper for the 2007 NSAC Long Range Plan

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I. INTRODUCTION

A. Overview

The LHC will open a new frontier in the study of strongly interacting matter under extreme conditions by providing heavy ion collisions at the highest energy ever achieved in the laboratory – an energy that will likely not be exceeded in the foreseeable future. The LHC is expected to produce quark gluon plasma at initial temperatures $>$ 4 times the QCD critical temperature. Some of the key questions to be addressed by the LHC heavy ion program are:

a. What is the mechanism for initial particle production at the LHC? Is the picture of particle production from a saturated initial state correct?

b. How does this initial matter evolve and thermalize/isotropize? Does it do so as rapidly as in Au+Au collisions at RHIC?

c. What are the quasi-particles of the quark-gluon plasma?

d. Can we use jet quenching and high-energy real and virtual photons to quantitatively probe the properties of and evolution of the quark gluon plasma?

e. Does the quark-gluon plasma screen heavy quarkonium (especially Upsilon) states?

f. How does the quark gluon plasma hadronize?

The ATLAS heavy ion (ATLAS-HI) physics program will provide data that can help answer all of these questions though the strengths of the ATLAS detector will best match the first five questions. As will be described below, ATLAS provides unique capabilities in the measurement of jets and photons. These probes will likely be essential to answering questions *c* and *d* and possibly *a* and *b* as well. The US ATLAS heavy ion (USATLAS-HI) program is designed to use the strengths of the ATLAS detector to answer the key physics questions above. The rest of this documents outlines the ATLAS-HI program, the advantages provided by the ATLAS detector and the role and expected impact of the US ATLAS heavy ion program.

B. ATLAS-HI Physics Program

In the Heavy Ion Letter of intent submitted to the LHCC in 2004, ATLAS identified the following primary goals of the ATLAS-HI physics program.

1. Studies of the bulk properties of the initial state and early time evolution of the matter created in heavy ion collisions through measurements of produced particle $dn_{\mathrm{chg}}/d\eta$, $dE_T/d\eta$ and v_2.

2. Studies of the energy loss and propagation of energetic partons in the quark gluon plasma through measurements of single high-$p_\perp$ particle production, single jet production and fragmentation, and multiple jet or γ/Z-jet events.

3. Studies of Debye screening of heavy quarkonium states in the quark gluon plasma via measurements of Upsilon production and J/ψ production.

4. Studies of parton saturation in nuclei at low x via measurements of hard processes at moderate $p_\perp$ in proton-nucleus and nucleus-nucleus collisions.

While ATLAS will also be able to measure fluctuation observables and study the physics of hadronization via measurement of neutral strange hadron decays and measurement of π^0/hadron ratios, these measurements are considered secondary to the primary goals listed above. Those primary goals are motivated by the key physics questions from the previous section, by results from the RHIC program and by the strengths of the ATLAS detector which are described below. All of the listed primary physics goals will require baseline measurements in p+p collisions, and the ATLAS heavy ion working group intends to directly participate in p+p measurements needed for the heavy ion physics program.

Each of the primary physics goals listed above may involve a number of separate measurements. In particular, the study of jet quenching and jet propagation in the QGP can take advantage of a large number of different jet measurement techniques and jet observables accessible using the ATLAS detector. We list here some of the most important high-$p_\perp$/jet measurements that ATLAS is intending to make.

- Single high-$p_\perp$ charged hadron and π^0 production.
- High-$p_\perp$ single muons from semi-leptonic decays of heavy quarks.
- Prompt isolated photon and Z production
- Single jet production
- Hadron p_L, $p_\perp$, and angular distribution in jets
- B jets tagged by displaced vertices and muons
- Hard radiation associated with jets and jet sub-structure
- Di-jet angular correlations and double fragmentation functions
- γ-jet angular correlations and γ-tagged fragmentation

The observation of jet quenching has been one of the most visible successes of the RHIC program, but the goal of using jet quenching as a tomographic probe of the medium has been difficult to achieve at RHIC. This is largely due to the low rate of hard processes at RHIC (relative to the LHC) and the large soft hadron background that prevents full jet reconstruction. When full jets can be detected, the effects of geometric bias that are so pervasive at RHIC will be substantially reduced. Assuming that radiative energy loss dominates for jet energies in excess

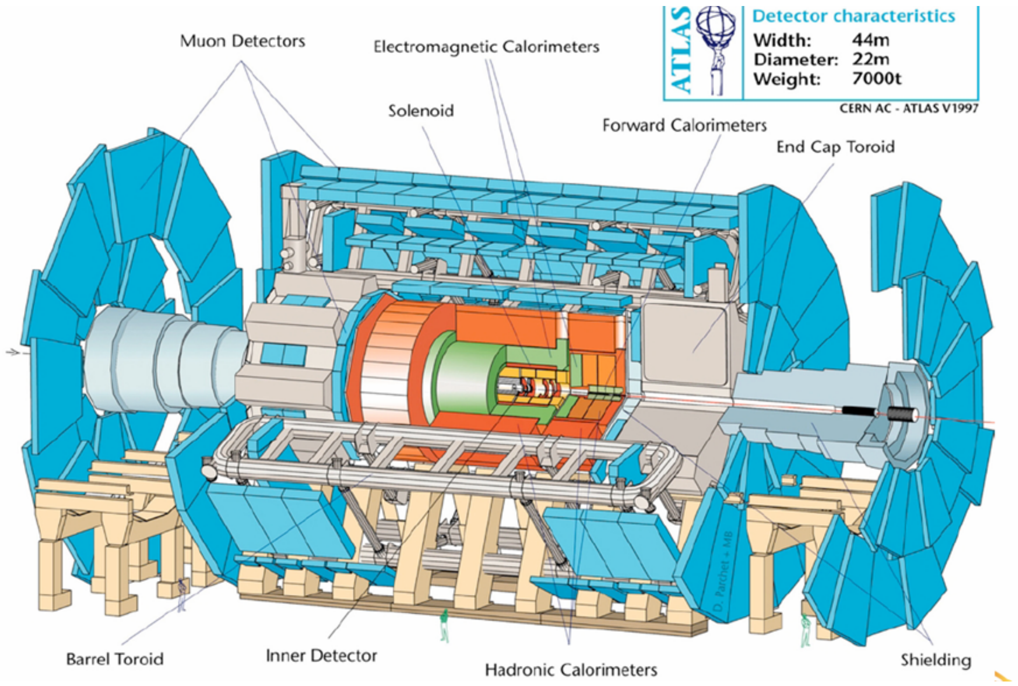

FIG. 1: Schematic of the ATLAS central detector

of 100 GeV (e.g.), such jets will still be clearly detectable in central Pb+Pb events even if they lose 50% of their energy. The direct measurement of hadron fragments within the reconstructed jets at the LHC will provide much more direct information on medium-induced energy loss than the measurements of single hadron $p_\perp$ spectra and di-hadron correlations at RHIC. With high statistics afforded by the LHC and the improved systematics provided by complete jet reconstruction, jet tomography of the quark gluon plasma may be finally realized. Then, jet measurements may provide much more detailed and quantitative probes of the properties of the quark gluon plasma.

Photon-jet measurements will be possible at the LHC as long as the prompt photons can be properly identified. ATLAS brings unique capabilities to the measurement of prompt photons as described below. Measurement of bremsstrahlung photon radiation (real and/or virtual) from jets would allow direct observation of the radiation resulting from jets interacting in the medium and would provide the most direct insight onto the interaction of the scattering parton in the medium. With its fine-grained calorimetry, ATLAS should be able to measure single energetic photons even when they are emitted within a jet.

System	η coverage
Silicon tracking	$\|\eta\| < 2.5$
EM Calorimeter	$\|\eta\| < 3.2$
Hadronic Calorimeter	$\|\eta\| < 5$
Muon spectrometers	$\|\eta\| < 2.7$
Zero-degree calorimeters	$\|eta\| > 8$

TABLE I: Table showing the rapidity coverage of various detector systems in ATLAS

C. ATLAS Detector Strengths

A schematic of the ATLAS experiment is shown in Fig. 1. The ATLAS central detector consists of an inner tracking system, electromagnetic and hadronic calorimeters, and external muon spectrometers. The inner tracker contains silicon pixel, silicon strip, and a straw-tube transition radiation detectors. All of these detectors cover 2π in azimuth. The rapidity acceptance of the central detector subsystems is listed in Table I. The central ATLAS detectors are complemented by two zero-degree calorimeters and forward luminosity monitoring detectors that will measure particle multiplicity in the region $5.25 \leq |\eta| \leq 6$. The zero degree calorimeters are being constructed by the Brookhaven heavy ion group (White) in close collaboration with the Yale high-energy physics group.

ATLAS is designed for high-rate detection of rare events and has a three-level trigger system capable of triggering on jets, photons, high-$p_\perp$ hadrons and muons. Although ATLAS was originally intended for relatively low-multiplicity p+p collisions it was designed handle on average 20 simultaneous p+p collisions per crossing during high-luminosity p+p operation of the LHC. The multiplicity of central Pb+Pb collisions is expected to be $\sim$ 10 times higher the typical multiplicity during high-luminosity running. Nonetheless, occupancy of all detectors except the transition radiation tracker (TRT) will be sufficiently low that they can be used for making heavy ion measurements with only modest degradation in performance.

The key strengths of the ATLAS detector for heavy ion measurements are

- Large acceptance, finely grained electromagnetic calorimetry with longitudinal (i.e. radial) segmentation

- Large acceptance, finely grained hadronic calorimetry with longitudinal segmentation

- Large acceptance muon spectrometers with separate momentum analyzing toroidal magnets
- Precision silicon pixel and strip inner tracking
- Data acquisition and trigger system

The combination of large acceptance, fine transverse segmentation, and longitudinal segmentation of the ATLAS calorimeters, particularly the electromagnetic calorimeters, are a clear advantage for ATLAS in the measurement of jets and prompt photons in heavy ion collisions.

The segmentation of the ATLAS calorimeters in different pseudo-rapidity intervals is shown in Table II. And a schematic of the barrel EM calorimeter illustrating the longitudinal segmentation is shown in Fig. 2. ATLAS is the only detector with a longitudinally segmented EM calorimeter. This is important because many hadronic showers start in the electromagnetic calorimeters and the longitudinal segmentation dramatically improves the experimental separation between electromagnetic and hadronic showers particularly in the presence of heavy ion background. The longitudinal segmentation helps improve the energy resolution of hadronic showers that start in the EM calorimeter. As a result ATLAS has the best intrinsic energy resolution for jet measurements among ALICE, ATLAS, and CMS.

The longitudinal segmentation also provides crucial benefits when reconstructing jets in the background of heavy ion events. Much of the soft background from the underlying heavy ion event will be attenuated prior to the second sampling layer of the EM calorimeter so the jet profile in the second sampling layer is subject to smaller fluctuations from the underlying background. Because the third sampling layer of the calorimeter is so clean, it can still be used to distinguish between electromagnetic and hadronic showers in the EM calorimeter.

The granularity of the first sampling layer of the ATLAS EM calorimeter is such that the typical particle occupancy per cell in the barrel is ≈ 0.15 for a Pb+Pb $dn/d\eta = 3000$ and the typical energy deposit in the cell is < 30 MeV. In contrast, electromagnetic showers typically deposit 1/3 of their energy in the first sampling layer so photons and electrons with energy above 1 GeV area easily detectable above the background. For photons with energy > 10 GeV, the first sampling layer of the ATLAS EM calorimeter is effectively free from the effects of soft hadron background. The segmentation of the first EM sampling layer was chosen by ATLAS to maximize the rejection of photon pairs from neutral hadron decays in $H \rightarrow \gamma\gamma$ searches. EM showers from single photons have a width (σ) of less than one η strip (cell) and close photons from π^0 and η decays can be rejected by observation of increased width of the pulse in the η

Section	η interval	Type	Cell size ($\Delta\eta \times \Delta\phi$)		
			Sample 1	Sample 2	Sample 3
Barrel	$\|\eta\| < 1.5$	EM	0.003×0.1	0.025×0.025	0.05×0.025
Barrel	$\|\eta\| < 1.7$	Hadr	0.1×0.1	0.1×0.1	0.2×0.1
Endcap	$1.5 < \|\eta\| < 2.5$	EM	*variable* $\delta\eta \times 0.1$	0.025×0.025	0.05×0.025
Endcap	$2.5 < \|\eta\| < 3.2$	EM	0.1×0.1	0.1×0.1	
Endcap	$1.5 < \|\eta\| < 2.5$	Hadr	0.1×0.1	0.1×0.1	0.1×0.1
Endcap	$2.5 < \|\eta\| < 3.2$	Hadr	0.2×0.2	0.2×0.2	0.2×0.2
Forward	$3.2 < \|\eta\| < 5$	Hadr	$\approx 0.2 \times 0.2$	$\approx 0.2 \times 0.2$	$\approx 0.2 \times 0.2$

TABLE II: Table showing ATLAS hadronic and electromagnetic calorimeter segmentation for different pseudo-rapidity intervals. The $\Delta\eta$ segmentation in the electromagnetic Endcap first sampling layer (marked variable) ranges from 0.003 to 0.006 over the specified η interval

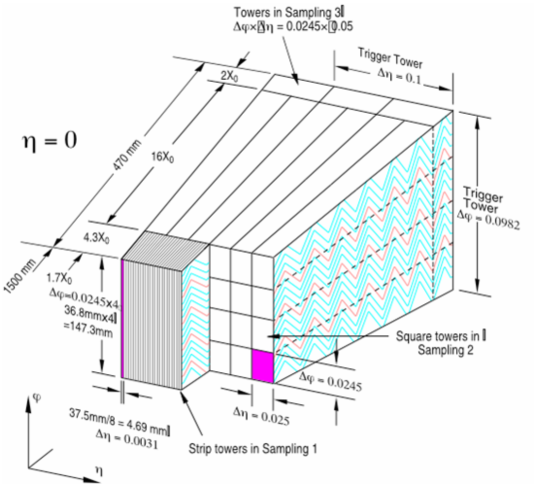

FIG. 2: Schematic of the ATLAS barrel EM calorimeter showing the longitudinal segmentation.

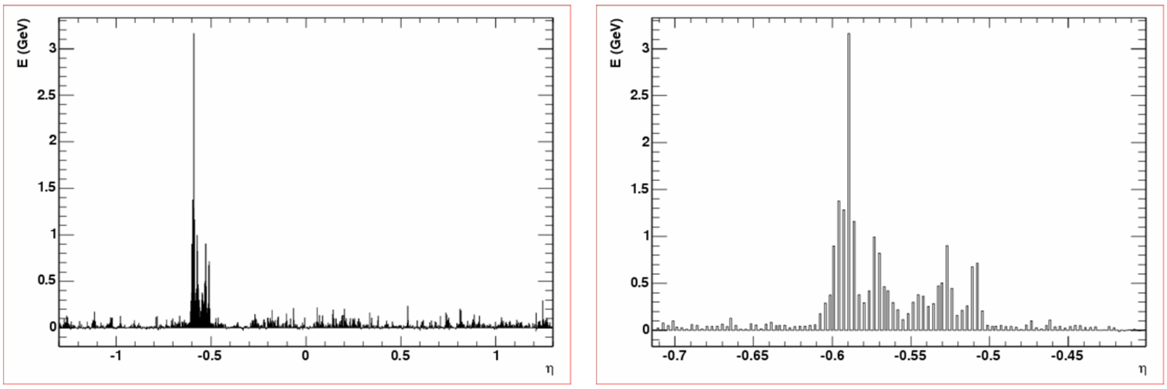

FIG. 3: Plot of the energy deposition per cell in a $\Delta\phi = 0.1$ slice of the first layer of the ATLAS barrel EM calorimeter for a Pythia simulated jet event superimposed on a $b = 2$ fm HIJING Pb+Pb event. The plot on the right is shown over a restricted η interval containing the jet.

direction in the first sampling layer. The ability of reject such decays is a clear advantage in carrying out prompt photon measurements. In addition, the first layer helps in applying jet isolation cuts because photons from other neutral hadrons in a jet will also be clearly visible above the background in the first EM layer. An example event is shown in Fig. 3 where a jet is superimposed on a $b = 0$ HIJING Pb+Pb event. The figure shows one ϕ row of the first EM layer in the barrel. Several EM showers associated with the jets are clearly visible and the background from the underlying HIJING event is effectively negligible.

D. Critical Analysis tasks

In order to accomplish the physics goals outlined in Section I B the ATLAS heavy ion working group is evaluating the performance of existing ATLAS analysis software on Monte-Carlo simulations of heavy ion events and is developing new tools to solve heavy ion specific problems. The most critical analysis/studies are listed below.

1. The measurement of charged particle multiplicity and $dn_{\mathrm{chg}}/d\eta$ using the pixel detectors.
2. Studies of the reconstruction of electromagnetic and hadronic E_T and $dE_T/d\eta$.
3. Reaction plane angle measurement using calorimeters and silicon detectors.
4. Silicon tracking performance in heavy ion collisions and at large $p_\perp$.
5. Development and study of calorimeter background subtraction procedures and effect of background fluctuations on jet position and energy resolution.

6. π^0 and η reconstruction inside and outside of jets
7. Prompt isolated photon reconstruction efficiency and neutral hadron background rejection.
8. Muon reconstruction and effects of heavy ion multiplicity on the association of muon spectrometer tracks with inner detector tracks.
9. Reconstruction of displaced vertices from B decay, efficiency and light quark/gluon jet rejection.

These analysis topics do not necessarily directly map onto specific physics measurements since many of the measurements that we wish to make will require a combination of these analysis tasks. Nonetheless, in order to accomplish the physics goals outlined in Section I B, the above analysis goals must be completed prior to the start of heavy ion operation of the LHC or at least brought to the point that we have the necessary tools to analyze the data and apply necessary efficiency and acceptance corrections (e.g.).

If the ATLAS heavy ion working group was forced to start from the beginning on all of the analysis topics, completing all of these goals prior to the start of heavy ion operation of the LHC would be a forbidding task. Fortunately, we are able to take advantage of the expertise of and analysis tools developed by the rest of the ATLAS collaboration. The ATLAS heavy ion working group has made the strategic decision to integrate our analysis tools into the standard ATLAS analysis framework (ATHENA) so that we could take advantage of track reconstruction algorithms, jet reconstruction algorithms, detector calibration procedures, etc. This decision initially introduced significant delay in progress on the above analysis efforts while the members of the heavy ion group learned how to work within the complicated ATLAS analysis framework. However, in the last six months it has resulted in rapid progress on many of the above analysis goals because we have been able to collaborate with and/or take advantage of the efforts of the much larger ATLAS collaboration to make rapid progress on the first five items in the list above. Thus, although ATLAS has the smallest number of physicists dedicated to the heavy ion physics program of the three LHC heavy ion experiments, we are confident that we will be prepared to use Pb+Pb collision data to address the physics goals laid out in Section I B.

Institution	FY07 FTEs	FY08 FTEs	FY09 FTEs	FY10 FTEs
Brookhaven	5.4	5.8	5.8	5.8
Columbia	2.9	3.5	5.1	5.6
Iowa State	1.4	2.4	3.6	4.1
Stony Brook	2.8	3.0	3.8	4.0
Total FTEs	12.5	14.7	18.3	19.5
# authors with Ph.D	19	19	20	22
Ph.D students	1	2	5	6

TABLE III: Projected level of effort on USATLAS-HI program at the four primary US institutions for the next four fiscal years.

II. USATLAS-HI PROGRAM

A. Level of effort

Four US institutions are now making substantial contributions to the ATLAS-HI program, Brookhaven National Laboratory, Columbia University, Iowa State University, and SUNY Stony Brook Chemistry. Currently 22 physicists, including 2 Ph.D. students are participating in ATLAS at these institutions. These numbers will grow over the next 3 years. Table III shows projections of the expected effort dedicated to the ATLAS heavy ion program at these four institutions. These levels of effort are determined by guidance from the DOE and are not considered optimal. The opportunity provided by the ATLAS heavy ion program has stimulated one new faculty position already and two more positions are currently under consideration. With such new positions, we would be able to support additional Ph.D. students. We also note that additional institutions are considering joining the ATLAS heavy ion effort. NYU is proposing to join and participate in the construction and operation of the ATLAS zero-degree calorimeters.

B. Physics and analysis priorities

The US groups within the ATLAS heavy ion working group are focused on the primary physics goals list in Section I B and have identified analysis topics designed to achieve these goals. These address items 1-8 in the list of critical analysis tasks from Section I D. The breakdown of the efforts at the four institutions is as follows

- Brookhaven: charged particle reconstruction, charged particle $dn_{\mathrm{chg}}/d\eta$ measurement, jets, low-x physics.
- Columbia: $dE_T/d\eta$ measurement, jets, photons
- Iowa State: Muon reconstruction
- Stony Brook: Reaction plane measurement, charged particle reconstruction, jets

We note that a new group is now being formed at Brookhaven consisting of former members of the PHOBOS, BRAHMS, and RHIC ZDC groups that will be lead by Videbaek.

The division of effort at the institutions largely follows the expertise and physics leadership established by the groups and their members in the RHIC program. Members of the Brookhaven ATLAS group have expertise drawn from PHOBOS in the use of Si detectors for measuring charge particle multiplicity and members drawn from BRAHMS have expertise in charged particle tracking in a high-multiplicity environment. Members of the Brookhaven and Stony Brook groups have extensive experience in the analysis of elliptic flow observables. Members of the Columbia group and the Stony Brook group have expertise in the study of high-$p_\perp$ hadron production and jet quenching measurements at RHIC. Members of the Brookhaven group have expertise in using heavy ion and p/d-A data to assess the possible role of parton saturation in inclusive particle production and moderate $p_\perp$ particle production at forward rapidities.

As noted above, the reconstruction of and analysis of jets is the most involved of the physics goals listed in Section I B. A complete analysis of jets even without addressing the special topic of b-tagged jets requires reconstruction of jets in the calorimeters, association of reconstructed charged particles with the jets, analysis of jet correlations and jet sub-structure etc. Therefore, it is appropriate that Brookhaven, Columbia, and Stony Brook work together on this particular topic. We have carried out a detailed analysis of the level effort required for ATLAS to be prepared to carry out jet analyses on data and to produce first jet results within six months of data-taking. We concluded that we need a total of 18 physicist-years working under typical RHIC conditions of 1/2 time effort devoted to data analysis in order to be ready to extract jet physics from a 2009 LHC Pb+Pb run. With the effort available from the combination of US and non-US institutions, we have more than sufficient physicists within the institutions participating in jet analyses to meet this requirement. However, the Brookhaven, Columbia, and Stony Brook groups are already working closely together, and **the combination of the jet analysis efforts of three groups will result in clear US leadership of jet analysis efforts within the**

ATLAS heavy ion program.

C. US Physics Visibility and Leadership in ATLAS-HI

For each of the physics goals listed in Section I B and each of the analysis topics listed in Section I D, the US groups within ATLAS include some of the most experienced and visible leaders from within the RHIC community. **Therefore, we expect the US institutions to provide strong leadership of these analysis efforts within the world-wide ATLAS collaboration**.

The expertise at Brookhaven and Stony Brook in the measurement of global variables and elliptic flow means that the US groups will provide strong leadership of these analysis efforts and the corresponding physics within the ATLAS-HI physics program. The construction of the ATLAS zero-degree calorimeters that will be essential for event characterization and the measurement of global physics observables in heavy ion collisions is being led by White at Brookhaven who was primarily responsible for the construction of the RHIC ZDCs. Members of the Brookhaven group, led by Steinberg, have been working closely with the ATLAS Standard Model working group to plan the ATLAS minimum-bias p+p physics program so that the necessary baseline multiplicity, E_T and particle spectrum measurements that will be needed for the heavy ion program will be available.

As noted above, expertise is being drawn from Brookhaven, Columbia, and Stony Brook to measure jets and jet fragmentation. This team draws on extensive expertise in the study of high-$p_\perp$ physics from PHENIX (Columbia and Stony Brook), and PHOBOS and Brahms (Brookhaven) and is working together to develop the necessary background subtraction tools to carry out jet measurements using standard jet reconstruction algorithms and develop alternative tools that may be needed to find jets at moderate E_T. The Columbia heavy ion group has expertise in the analysis of direct photon production within PHENIX and the Columbia group is working to study the performance of and adapt the ATLAS prompt photon identification algorithms for the environment of Pb+Pb collisions.

Historically, the analysis of muons and quarkonium suppression in expected environment of Pb+Pb collisions has been led by physicists at CERN and Geneva. However, the Iowa State group has recently made substantial progress in understanding the reconstruction of muons using standard ATLAS muon reconstruction algorithms and it is expected that Iowa State will make clearly visible contributions to physics measurements involving muons.

The study of low-x physics at the LHC requires no unique analysis tools as it requires many of the same observables that are important to the heavy ion program. However, the use of these tools at moderate $p_\perp$ requires additional study and analysis of resolution and acceptance. For example, di-jets with large rapidity gaps are particularly sensitive to BFKL (as opposed to DGLAP) evolution effects. Such measurements can be made in p+p collisions in ATLAS using the $\Delta\eta = 10$ unit acceptance of the ATLAS detector and by detecting high-$p_\perp$ π^0 in the zero-degree calorimeter. Such measurements can access x values down to $10^{-6} - 10^{-7}$ and will provide first tests of our understanding of parton saturation at the LHC. However, these analyses require the measurement of jets with energies down to 10 GeV which is not a primary focus of the ATLAS p+p program. Brookhaven has clear expertise in low-x physics at RHIC, and is currently evaluating the physics performance of large Δy di-jet measurements that can be made during the first 14 TeV p+p run of the LHC. Proton-nucleus running is expected to take place at the LHC, but not in the first few years. By the time p+A running takes place, many of the primary results from the heavy ion program will be published and the US groups can turn attention to the p+A program. Columbia and Brookhaven have already expressed the intent to contribute to the analysis of p+A data from ATLAS.

D. Organization of ATLAS heavy ion program

ATLAS has established a heavy ion working group that is on par with the other physics working groups within ATLAS. The working group has two conveners, one from the US and one from Europe and the conveners serve for a term of two years. Cole became the US convener as of Oct. 2006 replacing Takai who was responsible for the initiation of the ATLAS heavy ion effort within the US and helped lead the preparation of the LHCC Letter of Intent in 2004. The ATLAS heavy ion working group meets in person/by VRVS at CERN several times a year during various ATLAS weeks and (since Oct. 2006) by phone at bi-weekly intervals between these meetings. Separate topical meetings on particular analysis topics are now being held that include both US and non-US institutions. So far, these topical working groups are being coordinated by physicists from the US.

As of April 2006, the ATLAS heavy ion groups within the US are organized under the USATLAS project at Brookhaven with Cole as program manager. The US groups meet weekly to coordinate efforts and share results. As a result of these meetings the efforts of the US groups are tightly coordinated. As a result of this coordination, in the last year the US groups within

ATLAS-HI have made rapid progress on many of the analysis topics identified in Section II B. Summaries of these results were presented by Steinberg at Quark Matter 2006. ATLAS-HI is now the process of writing a Physics Performance Report that establish the performance and unique capabilities of the ATLAS-HI program.

III. SUMMARY

The US ATLAS heavy ion program is focused on the primary physics goals identified by the Barnes committee for the LHC heavy ion program and on physics topics for which we expect the LHC heavy ion program to provide compelling science based on results from RHIC.

ATLAS provides clear advantages in the measurement of many of the critical observables in Pb+Pb collisions, particularly jets and photons. The large acceptance of ATLAS will allow the measurement of jets over 10 units of pseudo-rapidity and photons over 6 units of pseudo-rapidity. The ATLAS calorimetry, particularly the longitudinal segmentation of the EM calorimeters will give ATLAS clear advantages in the measurements of jets and prompt photons in the presence of background of soft particles.

The US institutions have identified the most important analysis topics that will accomplish the chosen physics program and take best advantage of the unique capabilities of ATLAS, and are working aggressively to make sure that ATLAS will be prepared for heavy ion physics running of the LHC. The experience and expertise of the US groups and the tight organization of the US efforts means that the US groups will provide strong leadership of the ATLAS heavy ion program. We expect the US groups to have a highly visible contribution to every physics result from the ATLAS heavy ion program and we expect that many of these results will be directly attributable to one of the US institutions. In particulr, the US will make highly visible contributions to the measurements of global observables and elliptic flow, jets and jet fragmentation, prompt photon production, quarkonium production, and lox-observables.