SCIENTIFIC/TECHNICAL REPORTING

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Name of recipient: **TRUSTEES OF TUFTS COLLEGE INC**

Attn: CHRISTINE Woodroffe

Project title: **Search for New Phenomena Using W/Z + (b)-Jets Measurements Performed with the ATLAS Detector**

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Note: There is no authorization distribution limitation such as patentable material and protected data with this Project.

1 Executive summary

The Project proposed to use data of the ATLAS experiment, obtained during the 2011 and 2012 data-taking campaigns, to pursue studies of the strong interaction (QCD) and to examine promising signatures for new physics. The Project also contains a service component dedicated to a detector development initiative.

The objective of the strong interaction studies is to determine how various predictions from the main theory (QCD) compare to the data. Results of a set of measurements developed by the Tufts team indicate that the dominant factor of discrepancy between data and QCD predictions come from the mis-modeling of the low energy gluon radiation as described by algorithms called parton showers. The discrepancies introduced by parton showers on LHC predictions could even be larger than the effect due to completely new phenomena (dark matter, supersymmetry, etc.) and could thus block further discoveries at the LHC. Some of the results obtained in the course of this Project also specify how QCD predictions must be improved in order to open the possibility for the discovery of something completely new at the LHC during Run-II. This has been integrated in the Run-II ATLAS physics program.

Another objective of Tufts studies of the strong interaction was to determine how the hypothesis about an intrinsic heavy-quark component of the proton (strange, charm or bottom quarks) could be tested at the LHC. This hypothesis has been proposed by theorists 30 years ago and is still controversial. The Tufts team demonstrated that intrinsic charms can be observed, or severely constrained, at the LHC, and determine how the measurement should be performed in order to maximize its sensitivity to such an intrinsic heavy-quark component of the proton. Tufts also embarked on performing the measurement which is in progress, but final results are not yet available. They should shade a light of understanding on the fundamental structure of the proton.

Determining the nature of dark matter particles, composing about 25% of all the matter in the universe, is one of the most exciting research goals at the LHC. Within this Project, the Tufts team proposed a way to improve over the standard approach used to look for dark matter at the LHC in events involving jets and a large amount of unbalanced energy in the detector (jets+$\not{E}_t$). The Tufts team has developed a measurement to test these improvements on data available (ATLAS 2012 dataset), in order to be ready to apply them on the new Run-II data that will be available at the end of 2015. Preliminary results on the proposed measurement indicate that a very high precision can be obtained on results free of detector effects. That will allow for better constrains of dark matter theories and will spare the needs for huge computing resources in order to compare dark matter theories to data.

Finally, the Tufts team played a leading role in the development and the organization of the $\not{E}_t$ trigger, the detector component needed to collect the data used in dark matter searches and in many other analysis. The team compared the performance of the various algorithms capable of reconstructing the value of the $\not{E}_t$ on each LHC collision event, and developed a strategy to commission these algorithms online. Tufts also contributed in the development of the $\not{E}_t$ trigger monitoring software. Finally, the PI of this Project acted as the co-coordinator of the group of researchers at CERN taking care of the development and the operation of this detector component. The $\not{E}_t$ trigger is now taking data, opening the possibility for the discovery of otherwise undetectable particles at the LHC.

2 Actual accomplishment and goal comparisons

The Project, proposed for a period of three years, was funded for a period of 11 months in order to synchronize Prof. Beauchemin's funding with the rest of the Tufts HEP group. It is built on the following main physics goals:

A- To provide precise measurements of observables sensitive to QCD radiation (parton shower, and their matching procedures to matrix elements) in order to reach a better understand of such effects affecting all processes at the LHC;

B- To provide a first observation of an intrinsic heavy-flavor component to the proton, as well as to experimentally assess the importance of heavy-quark masses in gluon-splitting processes using W/Z+b-jets events;

C- To search for new phenomena in jets+$\not{E}_t$ final states with the ATLAS Run-II data;

D- To develop and optimize HLT $\not{E}_t$ -trigger algorithms for higher pile-up conditions, to commission this trigger in Run-II, and initiate a participation to the Phase-I Upgrade of the ATLAS trigger system.

To concretely address these physics goals, the Proposal was to:

1- Measure both the absolute W+jets differential cross section and the W+jets to Z+jets differential cross section ratio (R_{jets}) as a function of a selection of kinetic variables sensitive to QCD radiation using both Run-I and Run-II ATLAS data;

2- Measure both the absolute W+b-jets differential cross section and the W+b-jets to Z+b-jets differential cross section ratio ($R_{\text{b-jets}}$) as a function of a selection of kinetic variables sensitive to gluon-splitting into heavy-flavor quarks and to intrinsic heavy-quark components of the proton using ATLAS Run-I data;

3- Use data-driven techniques to make predictions for the Standard Model contribution to a data sample consisting of events with a high transverse momentum (p_T) jet and a large amount of unbalanced momentum in the detector ($\not{E}_t$), and compare the predictions with ATLAS Run-II data;

4- Perform efficiency and rate comparisons for various algorithms attempting to reduce the effect of pile-up on the $\not{E}_t$ reconstructed at trigger level, and fine-tune these algorithms to optimize the rate vs efficiency figure-of-merit.

This list of tasks was designed for a three-years project. For the first funded 11 months of the Project, the PI proposed to perform the following sub-set of tasks:

A'- Complete the Run-I W+jets and R_{jets} measurements that were already in an advanced stage when the Project started;

B'- Bring the analysis of the second measurement close to approval within the ATLAS Standard Model group;

C-' Postpone the jets+$\not{E}_t$ search to another project, to be started in late 2015, when ATLAS Run-II data would be available;

D'- complete the $\not{E}_t$ trigger algorithm studies.

The first of these objectives was met, resulting in two papers both published in the European Physics Journal. About 40% of the second objective was completed. The design of the analysis, determining how the measurement must be made in order to optimize its sensitivity to an intrinsic quark contribution to the proton and its sensitivity to the impact of the mass of heavy-flavor quarks on gluon splitting, has been made. A phenomenological paper has been submitted to Physics Review D on this work. The analysis software has been written, including all systematic variations of the various corrections to be made to data and Monte Carlo distributions in order to reach meaningful measurement results. However, background estimates, data unfolding and combination of electron and muon channel results are still work in progress.

While the third global goal mentioned above (C-) was not under the scope of the 11-months Proposal (C'-) being reported here (because Run-II data-taking has not started yet), new ideas on how to further improve the sensitivity of jets+$\not{E}_t$ searches and to better use them to constrain new physics theories have been proposed by the PI in 2014. This led to the development of a data analysis, using the 2012 ATLAS dataset, in order to test these ideas before the actual Run-II jet+$\not{E}_t$ search gets started. The idea is to measure the ratio of Z$\rightarrow \nu\nu$+jets to Z$\rightarrow \ell\ell$+jets cross sections as a function of the Z-boson transverse momentum and to compare the results with the flat distribution corresponding to ratio of Z$\rightarrow \nu\nu$ and Z$\rightarrow \ell\ell$ branching ratios well-measured at LEP. The design of this measurement as well as its phenomenological and sensitivity studies have been completed. The measurement itself has been made in the electron channel, and is in progress in the muon channel. This work is on target for being completed on time for implementing its benefits in the Run-II jets+$\not{E}_t$ first search. During the 11 months research period being reported here, advances on the third global goal mentioned above have therefore been met beyond expectations.

Finally, the fourth objective (D'-) of the Project has been fully met as $\not{E}_t$ trigger algorithms have been implemented, tested and are currently running online. At the start of the Project, in April 2014, Prof. Beauchemin has been appointed co-coordinator of the ATLAS $\not{E}_t$ trigger group, a responsibility that has been renewed in 2015. In addition, graduate student Hyungsuk Son started his ATLAS authorship qualification in October 2014 on $\not{E}_t$ trigger service. As a consequence, Tufts not only played a major role in the performance estimation of the $\not{E}_t$ trigger algorithms for Run-II, but actively participated in the validation of the developed algorithms on cosmic data, the development of the $\not{E}_t$ trigger monitoring software, the development of the $\not{E}_t$ trigger menu, and in the $\not{E}_t$ trigger group organisation. From this work, the fourth objective of the Project has been met beyond expectations.

3 Project activities

3.1 W+jets and R_{jets} measurements

The measurements of both absolute W+jets differential cross sections and W+jets to Z+jets differential cross section ratios as a function of a selection of kinetic variables such as the transverse momentum of the leading and sub-leading jets, the rapidity of these two jets, the angular separation between them, etc., was proposed in order to test various QCD assumptions concerning parton emission, both in the soft and the hard part of the spectrum. These two sets of measurements yield a complementary sensitivity to various QCD effects. W+jets processes are quite sensitive to changes in parton shower configurations, choices of Parton Distribution Functions (PDFs) and approximations in matrix element calculations, but their measurements suffer from very large systematic uncertainties. Most experimental and theoretical systematic uncertainties cancel to a large extend in the W+jets to Z+jets cross section ratios, which are thus very precise, but they are also solely sensitive to differences in the mass scales between W and Z processes, affecting the amount of energy radiated by these processes into gluons.

A first set of such measurements using 2011 ATLAS data was already in a mature stage at the time of the Proposal of the Project and the objective was to bring these analyses to publication. This objective was met as measurements of W+jets absolute differential cross sections as a function of 34 different observables have been completed and published in the European Physics Journal, and the W+jets over Z+jets differential cross section ratios as a function of 18 observables have also been completed and published in the same journal. The Tufts team played a dominant role in this work, completing the analysis in the muon channel (unfolding and final systematic uncertainty estimates) for both measurements, providing the needed phenomenological studies to obtain an interpretation of the results, editing the R_{jets} paper, and largely dealing with the long ATLAS publication process for these papers.

The results revealed that many divergences between data and predictions, often as large as what can be expected from the most optimistic new physics scenarios, are actually due to some QCD mismodeling. The effect of parton shower on these deviations is determinant. One of the conclusion is that it is imperative to tune all parton shower models to data, after their matching to a matrix element calculation, not before. The matching scheme should be improved, especially by providing the first two radiated gluons from a full calculation rather than from parton shower approximation. Gluons PDF must also be improved to describe properly high rapidity jets. Finally, these measurements demonstrated that the impact of Next-to-Next to leading order corrections have been over-estimated and further theoretical development should rather come from a better modeling of the softer QCD radiation. It is essential to account for these conclusions if new physics get ever observed at the LHC in jetty events.

3.2 W+b-jets and $R_{b\text{-}jets}$ measurements

By the start of this Project, it has been realized that the W+b-jets and $R_{b\text{-}jets}$ measurements might be used to measure an intrinsic heavy-quark contribution to the proton, an hypothesis postulated 30 years ago, but the observation of which has been highly controversial up to now. Phenomenological studies on intrinsic charms have been performed by the Tufts team, in collaboration with a team from Dubna in Russia. These studies led to the demonstration that a W+b-jet measurement has no sensitivity to such an exotic PDF contribution, but that a $R_{b\text{-}jets}$ measurement can be highly sensitive to an intrinsic charm component of the proton. A design of the $R_{b\text{-}jets}$ measurement has been proposed that optimizes the sensitivity of the measurement to the intrinsic charm. One of the idea is to treat both c-jets and b-jets as signal, reducing by a lot the uncertainties on heavy-flavor jet energy measurements and efficiency corrections, two of the largest sources of impedance on the interpretation of the previous W+b-jets measurement results. This constitutes the bulk of a paper submitted to Physics Review D. An extension of this analysis, allowing to also reach a large sensitivity to the effect of heavy-quark masses in gluon splitting phenomena, is studied. The Proposal is to measure the transverse momentum, the rapidity and the multiplicity of the heavy-flavor jets when a) c-jets are treated as background (the typical approach adopted in previous W/Z+b measurements); and b) when both b-jets and c-jets are treated as signal, which is a novelty that will reduce uncertainties and increase sensitivity to the QCD effects mentioned above. A fourth observable, corresponding to the Feynman scaling variable reconstructed from the heavy-flavor jet system, is also proposed to be measured due to its large sensitivity to intrinsic charm. The thus designed analysis will provide a point of comparison to what has already been done in the past, together with providing results using new ideas that could enlighten once for all the effect of heavy-flavor tagging on W/Z+jets processes.

The data analysis software has been completely written and debugged, including accounts for the various systematic uncertainties affecting the various correction factors to be applied to data in order to obtain the measurement results. However the background estimates have not yet been obtained, nor the unfolding of the data distributions. Conclusions about the physics assumptions outlined above will therefore only come with the measurement results, later in 2015.

3.3 Search for new physics in jets+$\not{E}_t$ events

In the course of the year, the PI proposed improvements over the typical counting experiment with data-driven background estimates (pioneered by the PI), used in the latest two Run-I jets+$\not{E}_t$ searches and planned for Run-II similar analyses. These improvements have to be tested already with ATLAS 2012 data in order to be ready in time for the Run-II search to be carried in late 2015. The improvements rely on a precise measurement of the ratio of Z$\rightarrow \nu\nu$+jets to Z$\rightarrow \ell\ell$+jets cross section ratio as a function of the p_T of the Z-boson (or the $\not{E}_t$ in the case of Z$\rightarrow \nu\nu$+jets), and to its comparison to the LEP results on the ratio of Z$\rightarrow \nu\nu$ to Z$\rightarrow \ell\ell$ branching ratios. The advantage of such approach is to avoid fluctuations of the reference to which data are compared, and to essentially eliminate the dependence of the interpretation of the results on the large theoretical and experimental uncertainties affecting the signal modeling in the standard approach. In addition, the final results would be unfolded from any detector effect, thus allowing theorists to directly use the experimental results to contraints their ideas, saving huge computing resource needs.

The Tufts team performed a complete set of phenomenological studies showing that the above ratio can be highly sensitive to QED radiation from charged leptons and to the interference of this radiation with jets. A method to precisely measure these QED effects has been developed, together with a strategy on how to define the ratio in a way that minimizes these effects, increasing the sensitivity to new physics. These results serve as a basis for an ATLAS note and for the senior thesis of the Tufts undergraduate student that was mainly involved with this component of the Project. The proposed measurement has been performed in the electron channel and is in progress of being completed in the muon channel. Comparison with predictions have not yet been done, so the final conclusions still have to be established, but the current precision reached in the electron channel measurement is already at the 3% level, comparable to the precision obtained by the L3 collaboration, the best of the LEP direct measurements of the invisible width of the Z-boson.

3.4 $\not{E}_t$ trigger development

The Tufts team initially took the responsibility to study the impact on the $\not{E}_t$ trigger resolution of the extra material introduced in the tracker during the long LHC shutdown (the new B-layer), and its was found to be negligible. Tufts also had to study all possible $\not{E}_t$ trigger algorithms available and to decide which algorithm was performing better as a function of increasing luminosity (and pile-up) and to determine the expected trigger rate in order to design the trigger menu. These studies demonstrated that, surprisingly, the simplest algorithm (simple vectorial sum of calorimeter cells) was performing better than other algorithms designed to deal with high pile-up conditions. This observation initiated a large review of basic topocluster formation, noise cuts and calibration procedures in ATLAS. It also led to a $\not{E}_t$ trigger strategy in which all different algorithms run in parallel, allowing to test these finding on actual Run-II data. Tufts responsibilities increased as Prof. Beauchemin became the $\not{E}_t$ trigger co-coordinator for 2014-2015, reappointed for 2015-2016. Tufts thus played an active role in the development of performance studies, on the validation of the algorithms on cosmic data and on the development of the $\not{E}_t$ trigger menu. In addition, Mr. Son took an important role in the development of the $\not{E}_t$ trigger monitoring software, integrating it in the completely new ATLAS trigger monitoring software architecture. Finally, Prof. Beauchemin took charge of the $\not{E}_t$ trigger group organisation. At the dawn of the first 50 ns 13 TeV collision runs, the $\not{E}_t$ trigger has been fully developed and updated. Most of the bugs have been fixed and the $\not{E}_t$ trigger is operational.

Prof. Beauchemin and Mr. Son, together with two ATLAS collaborators, have developed a phenomenological model describing the $\not{E}_t$ at trigger level in different pile-up conditions, in order to build a tool to accurately predict $\not{E}_t$ trigger rates in various luminosity scenarios. That would allow to more reliably plan $\not{E}_t$ trigger menus well in advance, a key element for analysis and trigger strategies. This work is close to completion and an ATLAS internal note has been written. A publication will follow shortly. From preliminary results, it seems that $\not{E}_t$ trigger rates are a priori predictable from this phenomenological model for a large range of pile-up conditions within a factor of two with respect to the actual rate in the detector, which is a factor of five to ten better than the tool that is currently used in ATLAS for rate predictions.

4 Products

Prof. Beauchemin and Dr. Meoni published two papers, one on the W+jets measurements (Eur. Phys. J. C 75 (2015) 82) and the other on the R_{jets} measurement (Eur. Phys. J. C 74 (2014) 3168). The details of these two analyses have been reported in one 850 pages ATLAS internal note (ATL-COM-PHYS-2013-590). The phenomenology study on the sensitivity of the $R_{\text{b-jets}}$ ratio to intrinsic quark has been submitted to PRD (arXiv:1410.2616 [hep-ph]) and is waiting for acceptance. The work done on the Z$\rightarrow \nu\nu$+jets to Z$\rightarrow \ell\ell$+jets ratio has been detailed in an ATLAS internal note and in Mr. George Wojcik Tufts senior thesis.

Both Prof. Beauchemin and Dr. Meoni attended international conferences and physics workshops. In Summer 2014, they were both personally invited to the Jet vetoes and multiplicity workshop held by theorists at IPPP Durham in UK. Prof. Beauchemin was also invited at the Frontier of QCD workshop in Mumbai, India, as well as a in few universities to give a seminar on QCD at the LHC (Tata Institute, Umass Amhearst, Sussex University). He finally chaired a session at the ATLAS hadronic workshop in Munich, Germany. Dr. Meoni contributed to the organization of the ATLAS Standard Model workshop held in Annecy in February 2015, where she also chaired a session. She was also invited to give a presentation at the CERN theoretical division in March 2015. In addition, the W+jets and R_{jets} results have been presented in many international conferences by other members of the ATLAS collaboration, including ICHEP 2014.

The work done by Prof. Beauchemin and Mr. Son on the $\not{E}_t$ trigger activities was presented and discussed in the ATLAS 2014 hadronic workshop. A conference note on the ATLAS trigger performance with early data is in preparation and two posters will be presented in international conferences in Summer 2015. As mentioned above, the phenomenological studies of the trigger-level $\not{E}_t$ in different pile-up conditions has been detailed in an internal ATLAS note and a publication is under preparation. Finally, Mr. Son contributed to the software development of the $\not{E}_t$ trigger monitoring system, currently used in the actual data-taking test runs.

No websites, technologies, inventions, patent applications, licenses and other products have been produced with this Project.

5 Computer modeling

This project does not include computer model development.