UNIVERSITÉ PIERRE ET MARIE CURIE

Pre-thesis internship report

Analysis of top events in ATLAS

Author:
Guillaume LEFEBVRE

Supervisors:
Mélissa RIDEL
Sophie TRINCAZ-DUVOID

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Abstract

This report introduces the work planned for the internship in the ATLAS team of the *Laboratoire de Physique Nucléaire et des Hautes Energies* (LPNHE), supervised by Mélissa Ridel and Sophie Trincaz-Duvoid. This internship is not only a part of the "NPAC" Masters 2 degree, but also a first experience before a possible PhD project. The aim of the internship is to find a good selection of $t\bar{t}$ events in dilepton channel, needed for further studies on the b-jet energy scale.

Contents

1 Introduction

1.1 The Large Hadron Collider (LHC) and the ATLAS experiment

Since the end of 2009, the Large Hadron Collider has been delivering data to its related experiments. This accelerator is a 27 km circumference proton-proton collider, located in the tunnel of the former LEP (e^+e^- collider), at the *European Organization for Nuclear Research* (CERN) near Geneva. It has been designed to collide protons with a nominal centre of mass energy of $14\ TeV$ and a nominal luminosity of $10^{34}\ cm^{-2}s^{-1}$, breaking Tevatron previous records.

The LHC installation includes 4 main detectors, each of them located at a different interaction point. LHCb is dedicated to B-physics and notably studies CP violation. ALICE records data from lead ions collisions, in order to characterise the quark-gluon plasma. Finally, ATLAS[1] and CMS are general particle detectors, with roughly the same goals. Their first priority is the search for the Higgs boson, the standard model particle which would explain the mass generation of weak bosons and elementary fermions. Another aim is to carry out precision measurements of electroweak parameters – such as electroweak mixing angle or coupling constants – to deeply test the validity of the standard model. A part of standard model studies also involve top quark physics with precise measurements on its intrinsic properties, such as spin, mass, or production cross section…The last main field of research is about physics beyond the standard model, where exotic theories, like supersymmetry or heavy gauge bosons, will be tested thanks to the highest energy in the centre of mass never achieved in any previous collider.

To fulfil this physics program, the ATLAS detector has been designed in consequence.

1.2 The ATLAS detector

The ATLAS detector first draws attention by its impressive dimensions: 25 meters high and 44 meters long. It is indeed the biggest LHC detector, twice as large as CMS for instance. It is a classic particle detector, with three main parts [1]. Around the interaction point, there is first the Inner Detector, which has been designed for precise tracking of charged particles, also giving information about particle momenta thanks to a surrounding $2\ T$ solenoidal field. Then come the electromagnetic (EM) and hadronic calorimeters, whose granularity are fine enough to allow good electromagnetic objects and jets reconstruction, but also a transverse missing energy measurement. The calorimeters are themselves surrounded by the Muon Spectrometer which detects muon and measures their momenta, in association with a superconducting toroidal coil, which delivers a magnetic field up to $7.5\ T$.

Since the collision rate is high (up to $40\ MHz$) and an event costs about $1\ MB$ of data storage, it is obviously impossible to keep all events. To reduce the total data flow without losing interesting physics events, a pre-selection filter has been developed. The ATLAS trigger system is organized into 3 levels. Each one uses partial or full informations from the different subdetectors to reduce the event rate with a finer and finer selection. At the end of the chain, a maximum rate of only $200\ Hz$ is stored for physics analysis.

The ATLAS detector has been designed to detect and distinguish different kinds of particles. The main outputs of the detector are electrons (identified by a track in the Inner

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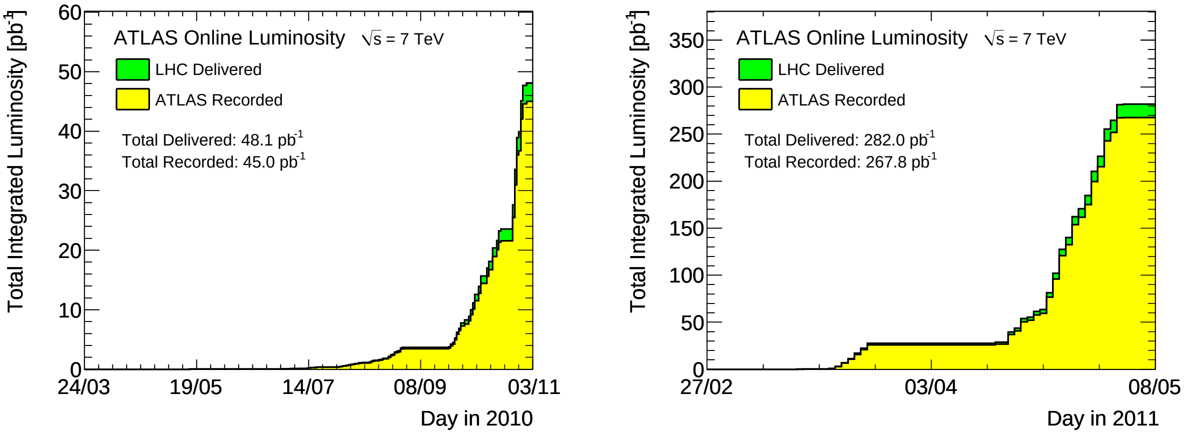
[1] ATLAS is the acronym for A Toroidal LHC ApparatuS

Detector and a shower in the EM calorimeter), photons (EM shower without track), muons (tracks in the Inner Detector and the Muon Spectrometer), jets (showers with tracks in the Inner Detector) and neutrinos *via* the measurement of the missing transverse energy called E_T^{miss} (which is the transverse momentum affected to final state invisible particles deduced from the detected particles momenta).

1.3 Current status and emulation

Since March 2010, ATLAS has been recording events with a $7\ TeV$ centre of mass energy. The instantaneous luminosity delivered is increasing with time, recently breaking the Tevatron record of $4.024 \times 10^{32}\ cm^{-2}s^{-1}$ [2]. With the current configuration, ATLAS already recorded more data whithin one month than during the entire previous year, as shown on figure 1 which represents the integrated luminosity recorded and delivered in 2010 and 2011.



(a) (b)

Figure 1: The total integrated luminosity delivered from LHC (green) and recorded from ATLAS (yellow) as function of the time in 2010 (a) and 2011 (b).

Even though the LHC performances are very good, the environment is still competitive. The Tevatron experiments, CDF and DØ, are still recording proton-antiproton collision data at $1.96\ TeV$ in the centre of mass frame, with a regular instantaneous luminosity. With the current features, the two experiments are expected to reach $\sim 10\ fb^{-1}$ of accumulated data by the end of the year, when the final shutdown of Tevatron should occur. It was previously planned that the LHC would stop at the end of 2011 for more than one year, to prepare the machine for $14\ TeV$ collisions. However, it has been recently decided to postpone the shutdown until the next year, in order to have enough data and to not miss a possible major discovery.

2 The LPNHE and the ATLAS group

The ATLAS experiment brings together almost 3000 physicists from 38 different countries throughout the world. This is hence one of the largest scientific collaboration ever seen. The *High Energy and Nuclear Physics Laboratory* (LPNHE) is one of the 174 laboratories involved in that collaboration.

The LPNHE is located on the Jussieu campus of the *Université Pierre et Marie Curie* (Paris 6). It depends on the latter, in addition with the *Université Denis Diderot* (Paris 7) and the *Institut National de Physique Nucléaire et de Physique de Particules* (IN2P3), which regroups 21 CNRS laboratories in France[3].

The middle-sized laboratory has the following staff repartition: 50 permanent researchers (23 academic and 27 CNRS), 48 technical and administrative staffs, 10 postdocs and 21 PhD students. Its field of research covers a large part of high energy physics, astroparticles and cosmology. In cosmology and astroparticle physcis, the groups are involved in experiments such as Supernovæ, HESS and AUGER, but also in the future projects LSST and CTA. In particle physics, researchers are actively working on ATLAS, CDF, DØ, BABAR, LHCb, ILD and T2K.

The ATLAS group, with 29 researchers, is one of the two largest teams of the laboratory. Its participation in the experiment covers many aspects, both in detector field (calorimeter construction and operation) and in physics analysis[4]. In hardware, the group is responsible for some parts of the electronics (control card for Front-End electronics and Front-End configuration). Besides, the group is participating in the global ATLAS software development: calorimeter reconstruction and calibration, identification of electrons and photons, and b-tagging are some examples. It is also involved in computing activities, by hosting for instance a node of the grid used for the simulation and reconstruction software of the ATLAS events. The team is moreover interested in the future of ATLAS, with an active participation to the Research & Development for pixel detectors for the high luminosity plan.

The ATLAS group of LPNHE is divided into subteams, with dedicated physics fields. Two of them work on physics analysis, respectively focusing on Higgs boson and top quark studies. The ”top quark subgroup“, in which the internship will take place, is made of 5 permanent researchers, 1 postdoc and 2 PhD students. Their analyses are about top mass and $t\bar{t}$ production cross section, looking essentially at the dilepton channel up to now. They are also involved in measurements realised with first LHC data as preliminary studies for top analyses: b-jet energy scale, efficiency on reconstructed electrons from J/Ψ and Z, and e^- production cross section from heavy quark decays.

3 Top cross section

The aim of the internship is to get familiar with the ATLAS analysis software by working on $t\bar{t}$ data. This analysis is related to the planned PhD subject, which will be dedicated to the measurement of the $t\bar{t}$ production cross section in the all-hadronic channel ($t\bar{t}$ decay into Wb and W's decay into quarks, see section 3.3). The understanding of $t\bar{t}$ physics is therefore useful to introduce the work that will be done during the next two months.

3.1 Generalities on top quark physics

The top quark was discovered by Tevatron experiments in 1995, confirming standard model predictions made 18 years before. The mass, given by the most recent combined analysis (CDF and DØ), is found to be $173.3 \pm 1.1\ GeV$ [5]. This is the heaviest quark of the three families by at least two orders of magnitude. Scientists pointed out that this mass has the same order of magnitude as the vacuum expectation value ($\sim 246\ GeV$) of the Higgs field, although nothing in the theory has been able to relate both so far. Nevertheless, the standard model predicts that the coupling to the Higgs is proportional to the particle mass. The top is thus a major contributor in Higgs interactions. Measuring the top mass with high precision would therefore add constraints on the Higgs mass, through radiative corrections computation.

Compared to other quarks, the high mass of the top leads to another specificity. Indeed, it is so heavy that it decays before hadronising. The top is therefore the only quark whose properties – e.g. its mass – can be directly measured.

3.2 Production of $t\bar{t}$ pairs

At LHC, the top quark is mostly produced in $t\bar{t}$ pairs, by strong interaction through gluon fusion or quark-antiquark scattering (see figure 2). Due to the centre of mass energy and the nature of the beams, the dominant process for the LHC is the gluon-gluon scattering ($\sim$ 90% of cases), while the situation is opposite at the Tevatron ($\sim$85% for the $q\bar{q}$ channel) [6].

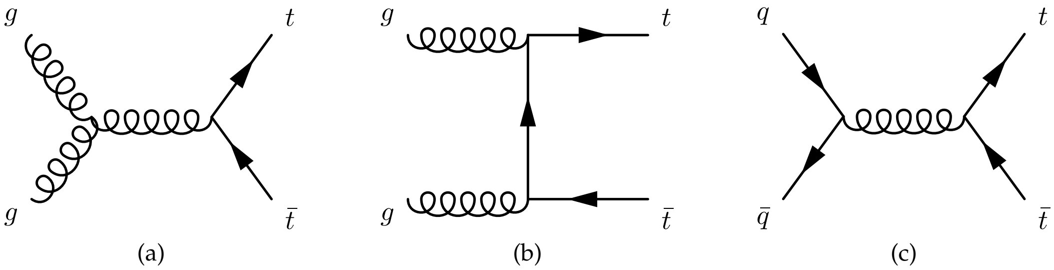


Figure 2: Diagrams of $t\bar{t}$ production at lowest order. The gluon-gluon scattering (a) and (b) are the dominant processes at LHC. Diagrams (c) represents the quark-antiquark scattering channel.

The articles [7, 8, 9] show that one of the LHC priorities of the top studies is to measure the $t\bar{t}$ production cross section with high precision. The motivations behind this are multiple: it is first a deep test of QCD perturbative theory at quark level, as it is not directly known for lighter quarks because of the confinement issue. The validity of the theory would thus be checked by comparing the measurement with the value predicted by the standard model. The other main reason for a precise measurement is the importance of $t\bar{t}$ production in other studies. Indeed, most of the tests for new physics scenarios rely on a good knowledge of that cross section, as it represents a major background for these analyses. One striking example is the search for a possible fourth generation of quark t'.

3.3 Top quark decay

According to the standard model, the top quark decays into W boson and b quark in almost 100% of the cases. The b then hadronises and produces a jet of particles. The W decays either leptonically or hadronically, giving respectively final states with a lepton-neutrino pair or with jets. By combining the different W decays, one can find three different channels of study:

Dilepton: the two W decay leptonically, giving two b-jets, two leptons and some missing transverse energy. This is a very clean channel due to the low background. It suffers however from low statistics due to the small branching ratio ($\sim 10\%$).

Lepton + jets: one W decays leptonically and the other hadronically, giving four jets with two b-jets (which can be identified or not), one lepton and some missing energy. Its branching ratio is about 44%.

All-hadronic: (see figure 3) the two W give jets, *i.e.* there are six jets in total with two b-jets. The statistics on this channel is higher due to the high branching ratio ($\sim 46\%$) but it is the hardest decay channel to identify due to a very important QCD multijets background.

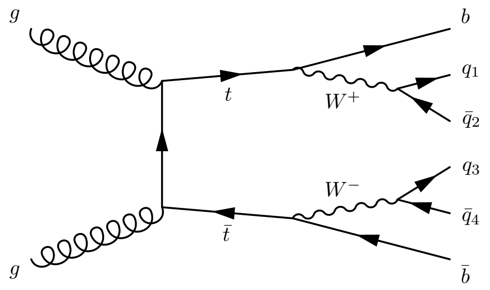


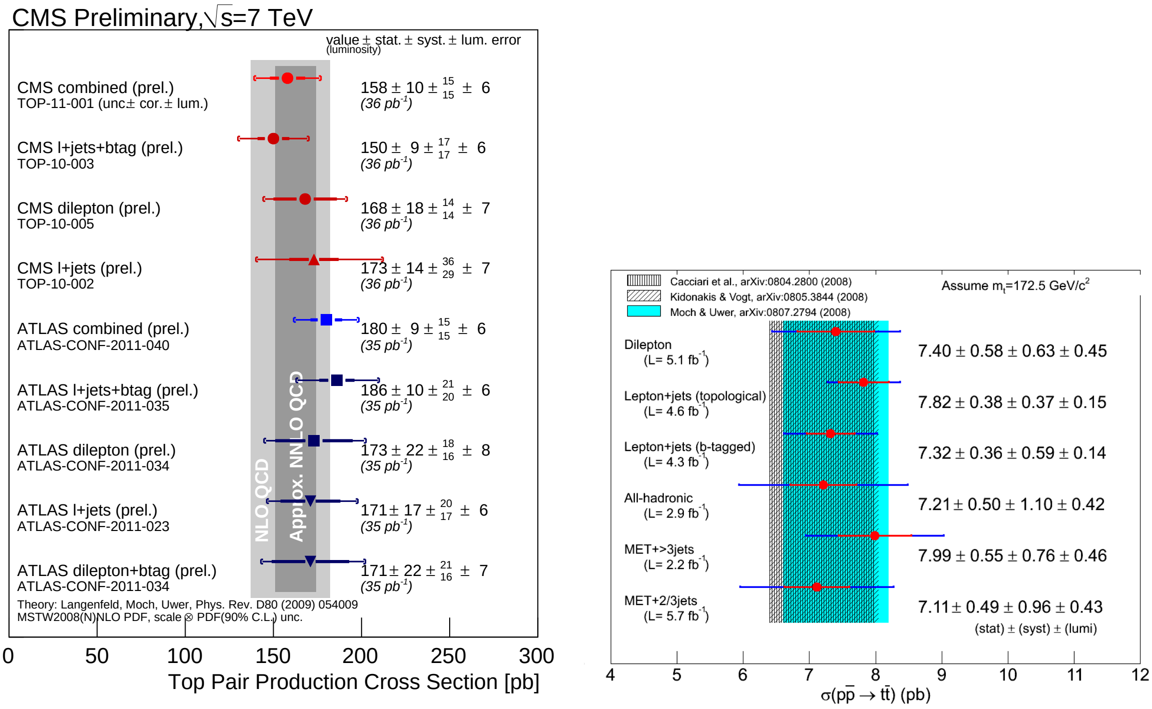
Figure 3: Diagram of $t\bar{t}$ decay in the all-hadronic channel.

3.4 b-jet identification

As $t\bar{t}$ decay gives b-jets in each channel, a good identification of them will play an important role for cross section analyses. This "b-tagging" process can be done with different methods, each time by looking for different characteristic properties. The article [6] explains the different methods for b-tagging in ATLAS. The first method relies on the fact that the b quark hadronisation produces most of the time a b-hadron carrying a large fraction of the total momentum. As this hadron is relatively heavy and has a long life time, its length of flight is large enough to be able to distinguish the vertex of its decay from the primary collision vertex. It is therefore possible to use the impact parameter measurement of the secondary vertex reconstruction to do the identification. Another identification method is to use a semi-leptonic decay of the b-hadron (which occurs in about 40% of the cases) by tagging the lepton in the jet. This is the so-called soft lepton tagging, the lepton being soft compared to high-p_T leptons from W or Z decays. In the end, it is possible to develop an algorithm that takes into account each method weighted by its efficiency.

3.5 $t\bar{t}$ production cross section

As previously seen, the $t\bar{t}$ cross section can be independently measured in the three different channels of decay products. By using the branching ratios predicted by the standard model, one can compute an inclusive cross section from each measurement and compare them with each other. ATLAS and CMS recently published preliminary results, which are shown in figure 4a. The analysis was made on dilepton and lepton + jets channels with about 36 pb^{-1} of data. All measurements agree with the standard model value of $165\ ^{+11}_{-16}\ pb$, found with Next to Next to Leading Order computations. This agreement is not fully satisfactory yet as the uncertainties are still quite large (about 10% for the ATLAS combined result). They should, however, be reduced in next analyses. For instance, the statistical error will be divided by about a factor 5 if the analysis is re-done with the 1 fb^{-1} of data expected by the end of the year 2011. Furthermore, the systematic error could be reduced with finer selections and a better understanding of the detector response, which will be possible using more and more available data.



(a) (b)

Figure 4: Results from $t\bar{t}$ cross section measurements in ATLAS and CMS (a) and CDF (b).

The Tevatron experiments also published their $t\bar{t}$ cross section measurements. Figure 4b shows the most recent results from CDF. The expected cross section is lower than the LHC value because both colliders have different configuration in centre of mass energy and in beam nature. It furthermore means that for the same integrated luminosity, the LHC statistics for $t\bar{t}$ production is larger. When LHC will be running at 14 TeV, the event rate will be 10 times higher than the one at the Tevatron, thus explaining the the so-called name of "top factory“.

A careful study of the different sources of uncertainties shows that the statistical error is larger for the dilepton channel due to the small branching fraction. The combined result weighted by the different uncertainties shows that the all-hadronic channel has a lower contribution due to its large systematic error. But one should note that the studies for this channel were realised with less data. With a higher integrated luminosity, the uncertainty should decrease enough to give a global error at the same level as the dilepton channel. Therefore, the all-hadronic channel cannot be neglected.

3.6 The all-hadronic channel specificities

Most cross section measurement studies have the same pattern: the aim is to distinguish signal events from background as precisely as possible. However, the method to get to this result is obviously not universal and needs to be adapted to each process. This section briefly describes the method used by ATLAS to find the $t\bar{t}$ cross section in the all hadronic channel [10].

The study starts by selecting events, which have the expected $t\bar{t}$ signature. To have a good selection of all-hadronic final state events, they should have no identified lepton, a very small missing energy and at least 6 jets with 2 b-tagged ones. The two first criteria are important because they minimize contamination from other $t\bar{t}$ channels.

Jets are reconstructed with the anti-k$_T$ algorithm which was developed by a french group of theorists [11]. The algorithm proceeds as followed: for each pair of topoclusters[2] i and j, two distances are computed

$$d_{ij} = \min\left(\frac{1}{{k_T}_i^2}, \frac{1}{{k_T}_j^2}\right) \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{R^2} \tag{1}$$

$$d_{iB} = \frac{1}{{k_T}_i^2} \tag{2}$$

where ${k_T}_i$, y_i and ϕ_i are respectively the transverse momentum, the rapidity and the azimuth of the entity i and R is a chosen radius parameter. If the smallest distance is one of the different d_{ij}, the corresponding clusters are combined by adding their transverse momentum. If the smallest distance is d_{iB}, the corresponding cluster is removed from the treatment. The distances are computed again, and this until there is no more cluster to be treated. The remaining objects are then considered as jets. With this definition, the algorithm tends to produce conical jets which also fulfil the safety requirements [6]. However, the jet energy at this stage needs to be corrected. Indeed, jets are the visible effects quark and gluon production in the detector but the total measured energy of the jets is not equal to the energy of the produced quarks and gluons, due to several effets. The different corrections, which can be sophisticated, are called the jet energy scale. A more detailed description is given in section 4.1

The next step in the analysis is to estimate the background in the selected sample. Here, the main contribution is QCD multijets background, which is very important at hadronic

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[2] A topological cluster is a calorimeter object corresponding more or less to a particle. Is it constructed from calorimeter cells thanks to an identification algorithm.

colliders. As the process is not precisely described by the theory, a Monte Carlo event simulation would not be sufficient enough. The background therefore needs to be estimated from real data. To do so, a larger selection is made, in order to use control samples. This selection requires events with at least 4 jets, without any lepton signature.

Once the data sample is determined, it is necessary to separate background from signal. The method used for this relies on a χ^2 discriminating variable, which compares combined invariant masses of jets with the W and top masses. The χ^2 is then minimized by taking the best jets combination. A number of signal event N_{sig} is extracted by taking the best selection on χ^2.

After listing all systematic uncertainties on N_{sig}, the inclusive cross section is finally computed with the following formula:

$$\sigma_{t\bar{t}} = \frac{N_{sig}}{\epsilon \times \int \mathcal{L}dt} \tag{3}$$

where $\int \mathcal{L}dt$ is the integrated luminosity and ϵ is a factor taking into account the branching ratio, the selection efficiency and the detector configuration, such as signal acceptance.

This analysis has been made recently by ATLAS with $36\ pb^{-1}$ of data. The result is $118 \pm 73\ (stat.) \pm 48\ (syst.) \pm 7\ (lum.)\ pb$, corresponding to a global uncertainty of $88\ pb$. With this large error, the result is poorly significant compared with the measurements made in other channels. The high statistical error is due to the difficulty of the χ^2 method to distinguish signal from background, but it should decrease with more data. Several sources of systematic error have been identified, and the main contributions come from b-tagging efficiency and jet energy scale, which is expected since b-tagging and jets are the main requirements of the all-hadronic channel selection. A better analysis of these effects would hence be useful to get more accurate results.

4 b-jet energy scale

One of the important parameters of the $t\bar{t}$ cross section measurement in the all-hadronic channel is the jet energy scale (see section 3.6). The goal of this internship is to work on a method developed at LPNHE to determine the b-jet energy scale.

4.1 Methods for jet energy scale measurements

The jet energy scale is an important concept, used by every physics analysis with jets in the final state. It is basically a tool that links the jet energy as measured in the calorimeter and the parton energy. The interesting information for physics analyses is indeed the parton at the origin of the jet. However, the measurement gives only access to the jets and the reconstructed energy may differ from the parton one. The jet energy scale hence corrects this by taking into account all known detector effects, such as the calorimeter response to different deposits, reconstruction effects, dead material, noise, pile-up, etc.

In ATLAS, the jet energy scale is still a dominant source of uncertainties in $t\bar{t}$ studies, mostly due to the insufficient knowledge of the calorimeter response to hadronic deposits. The jet energy scale may be determined in different ways, but all methods rely on the good knowledge of the electromagnetic scale[3]. The common method is to use different correction factors from data and simulation, which depend on the differences between electromagnetic and hadronic energy deposits in the calorimeter [12].

The jet energy scale can also be determined by *in situ* methods, which directly use data to calibrate the jets energy. A good example is the use of γ + jets events, which basically relies on energy-momentum conservation to calibrate the jet energy [13]. In this view, the direct measurement of jet energy is compared with the one which balances the well determined photon energy. The method has been successfully tested with Monte Carlo simulation.

The ATLAS collaboration recently estimated the jet energy scale systematic uncertainty by using a combination of both previous techniques [14]. They found a satisfying range from 2.3% up to 13.8%, varying with the reconstruction parameter R (defined in section 3.6), the jet transverse momentum and its pseudorapidity. However, it has been found that the jet energy scale is dependent on the initial parton type. The result is hence strongly dependent on the sample, and an additional systematic error needs to be added in case of other analyses. This uncertainty can be reduced if the jet composition of each studied sample is known, using then the flavour-dependent jet energy scale. The range given above for the the jet energy scale uncertainty has been evaluated for a mixture of light quarks and gluons [15]. Analyses involving b-jets usually add an uncertainty of 2.5% to the global jet energy scale [16] to take into account, in particular, the soft lepton produced by the b-hadron decay – as already mentionned –, but also the neutrino which escapes detection. The aim of the internship is to determine independently the b-jet energy scale on a b-jet sample to avoid the additionnal 2.5% systematic error used up to now.

4.2 Method developed for b-jet energy scale

At LPNHE, a particular work is currently done to characterise the b-jet energy scale by using $t\bar{t}$ dilepton events. The idea is to use these kind of event because they are relatively "clean" and could hence be considered as a pure b-jet sample. The aim of the study is to find the b-quark energy by kinematics constraints and compare it with the value given by the calorimeter, similarly to previous *in situ* methods. Even if the presence of two neutrinos causes a loss of kinematic informations (since it is impossible to distinguish both particles), the event remains kinematically constraint. The kinematic equations of the system are given by

$$\begin{aligned}
(P_{l^+} + P_\nu + P_b)^2 &= M_t^2 \\
(P_{l^-} + P_{\bar{\nu}} + P_{\bar{b}})^2 &= M_{\bar{t}}^2 \\
(P_{l^+} + P_\nu)^2 &= M_{W^+}^2 \\
(P_{l^-} + P_{\bar{\nu}})^2 &= M_{W^-}^2 \\
(P_{l^+} + P_\nu + P_b)^x + (P_{l^-} + P_{\bar{\nu}} + P_{\bar{b}})_x &= p_{t\bar{t}}^x \\
(P_{l^+} + P_\nu + P_b)^y + (P_{l^-} + P_{\bar{\nu}} + P_{\bar{b}})_y &= p_{t\bar{t}}^y
\end{aligned} \tag{4}$$

where P_i are the four momenta of each particle and $p_{t\bar{t}}^{x,y}$ are the transverse components of the $t\bar{t}$ momentum in the lab frame[4]. If the W and top masses are fixed to their well measured

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[3] The electromagnetic scale has been already studied by using test beam data plus corrections with the $Z \to e^+e^-$ process.

[4] $p_{t\bar{t}}^x$ and $p_{t\bar{t}}^y$ are not systematically zero, taking into account eventual initial state radiation.

values and the b energies are left as unknowns, the system leads to 6 unknowns and can therefore be solved.

The basis of this analysis relies on the determination of a good event sample, and this will constitute the work of the internship. Selection criteria and discriminating variables should be set to reject most of the background, even if it implies a signal loss. Besides, a good event reconstruction is required to avoid combinatorial background due to the misidentification of the decay products.

Obviously, event selection in dilepton channel is not brand new. The project could hence begin by taking inspiration from cross section and mass measurements, since the required samples are similar [7]. For instance, the different sources of background are already identified: the main contributions are leptons from QCD multijets, Z/γ* + jets and W + jets[5] events. Selection criteria could be also taken as a starting point, *i.e.*

- Two oppositely-charged leptons with a p_T threshold
- At least two jets with 2 b-tagged ones with a p_T threshold
- A high transverse missing energy to decrease Z/γ* + jets and QCD backgrounds
- A high dilepton invariant mass, also far from Z mass to respectively decrease b-quark decay and Z backgrounds

Of course, other criteria will be added to get a good purity. Furthermore, due to the particular aim of the selection (namely having a well identified b-jet sample), criteria determining which of the 2-jets and the 2 leptons come from the t or the $\bar{t}$ will be important.

This first work will be a good training to get used to the ATLAS software tools. In a second step, the selected events will be used to test the program developed at LPNHE, which solve the equation system 4 by using either real data or simulated events as inputs. In that case, the results will be compared with the true b-quark energy and will give the precision of this b-jet energy scale measurement.

5 Conclusion

The b-jet energy scale study has been started by using simulated $t\bar{t}$ events and developing the software of the method. Once it will be judged as promising, the next step will be to test it on real data. With that goal, the internship work will mostly concentrate on the determination of a satisfying pure $t\bar{t}$ sample. It will be used afterwards to find a good estimator of the b-jet energy computed from kinematics.

The systematic uncertainty of any $t\bar{t}$ production cross section in the all-hadronic channel is strongly dependent of the good determination of the jet energy scale. Therefore, the current work will hopefully be used during the planned PhD study of the $t\bar{t}$ production cross section in that channel.

This choice of PhD subject has firstly been motivated by the interest in the subject. The particular choice of the all-hadronic channel for the cross-section measurement is interesting for the ATLAS collaboration because it has not been deeply studied so far and, despite the large background and the difficulty of the measurement, major improvements are possible in that field. Moreover, it is strongly related to the work realised at LPNHE on calorimeter objects and particularly on the b-jet energy scale.

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[5] For W + jets background, one lepton comes from the W and the other is produced either by a b decay, a light hadron decay or by conversion in the detector.

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