

## QCD and Top Quark Physics at the LHC

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The expected performance of the ATLAS and CMS detectors at the Large Hadron Collider (LHC) in QCD and top quark measurements is discussed, with a focus on the early data taking phase. Such processes are amongst the primary backgrounds in the searches for new physics, and thus must be understood very well before discoveries can be made. In addition, they serve as useful detector calibration candles.

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## 1. Introduction

The prime goal of the ATLAS and CMS experiments at the Large Hadron Collider LHC at CERN is to find the Standard Model Higgs boson and to look for possible signatures of new physics beyond the Standard Model, such as Supersymmetry. However, before discoveries can be made, the detectors have to be calibrated, and the Standard Model backgrounds have to be understood. The LHC will produce QCD events with jets at a very high rate and with a wide kinematic range. In addition, the production cross section for top quark pairs is enhanced by two orders of magnitude compared with the Fermilab TEVATRON.

QCD jet and top quark processes will be used for Standard Model measurements and tuning of Monte Carlo (MC) generators. In addition di-jet and top quark final states are important tools for calibrating the detectors. In this article, the potential of ATLAS and CMS in the fields of QCD and Top Quark Physics is briefly summarized, with the focus on recently performed studies using the most recent simulation and reconstruction software of the experiments, and which are targeted at the first LHC data.

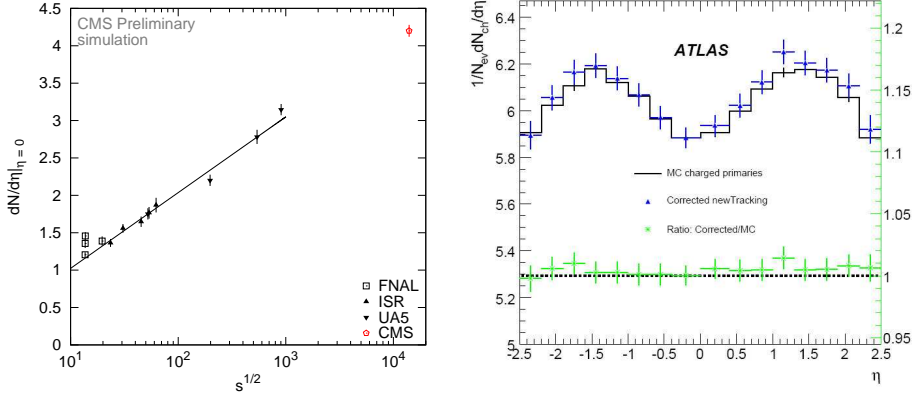
## 2. QCD Physics

QCD processes such as multi-jet production will occur at a very high rate, and in a kinematic range (high jet transverse momentum  $p_T$ , low Bjorken- $x$ ) which is considerably extended with respect to e.g. the Fermilab TEVATRON. The data can be used to measure jet cross sections and to place constraints on the parton density functions (PDFs) of the proton and on the strong coupling  $\alpha_s$ . At low  $p_T$ , Monte Carlo models for multiple interactions and the underlying event can be tuned, whereas at high  $p_T$ , deviations from the expected behavior may be due to new physics signals.

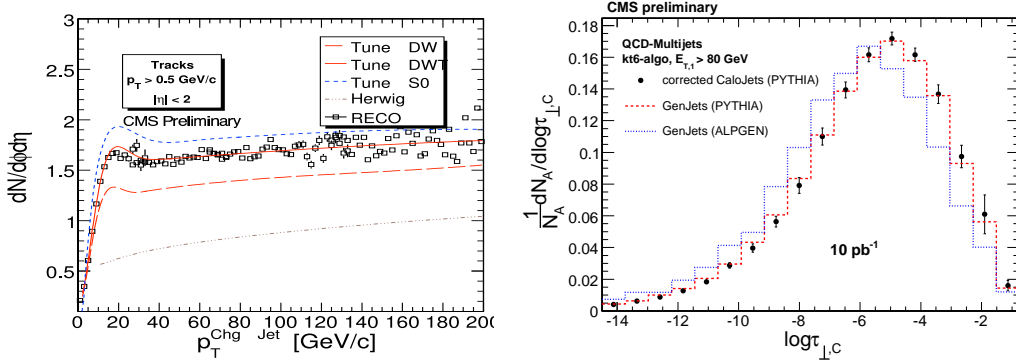
### 2.1 Low $p_T$ QCD

Cross sections and differential yields of charged particles produced at LHC energies can be measured with good precision with the ATLAS and CMS tracking detectors. In a recent CMS study [1], around 2 million simulated minimum bias events are used, corresponding to 1 Hz of trigger rate collected over a period of one month of data-taking. Tracks are reconstructed with transverse momenta as low as  $p_T = 75$  MeV using a dedicated pixel hit triplet seeding technique. The measured distributions are corrected for acceptance, trigger efficiency etc., and the systematic error is around 8%. Figure 1 (left) shows the projected measurement of the charged particle density at  $\eta \sim 0$ , which would allow to discriminate between models predicting either a  $\sim \ln(s)$  or  $\sim \ln^2(s)$  behavior. Figure 1 (right) shows a similar study by ATLAS [2] of a measurement of the charged particle density vs.  $\eta$  for  $p_T > 150$  MeV for non-single-diffractive events.

Measurements of the underlying event (defined as all activity but the hard scatter) at LHC energies are crucial for the understanding of multi parton interactions as well as for the tuning of Monte Carlo models. It can be studied by looking at the hadronic activity in the region transverse to the leading jet in the event. Extrapolations of existing models predict an activity which is two times higher than that at the TEVATRON. Figure 2 (left) shows the result of a CMS study [3] for  $10 \text{ pb}^{-1}$ . The plot shows the corrected charged particle density in the transverse region as a function of the



**Figure 1:** (left) Energy dependence of pseudo-rapidity density of charged hadrons at  $\eta \sim 0$  (CMS). (right) Corrected normalized charged particle pseudo-rapidity distribution for non-single-diffractive events (ATLAS).



**Figure 2:** (left) Corrected charged particle density in the transverse region as a function of the leading track jet  $p_T$  (CMS). (right) Central transverse thrust distribution for  $10 \text{ pb}^{-1}$  (CMS).

leading track jet  $p_T$ , where a high sensitivity with respect to the various available MC tunes can be observed.

## 2.2 High $p_T$ QCD

Both collaborations extensively study QCD jet production using the most advanced jet algorithms such as SIS-Cone [4] and Fast-Kt [5], using either calorimeter towers, tracks or particle flow objects as input to the jet finding. For the jet energy scale (JES) calibration, CMS uses a factorized multi-level jet energy correction approach [6], whereas ATLAS calibrates calorimeter clusters to the particle scale, which are then used as input for the jet finding. Both experiments optionally apply corrections to the parton level.

Dijet azimuthal decorrelations have been studied by ATLAS [7], by looking at the difference in  $\phi$  between the leading two jets in dijet events. This quantity is very sensitive to gluon radiation and higher order effects, and allows tuning of MC models.

Normalized event shapes, using collinear and infrared safe observables, are robust against JES uncertainties and are thus suitable for the early data analysis. Figure 2 (right) shows a projection for  $10 \text{ pb}^{-1}$  of CMS data [8] of the corrected central transverse thrust distribution for jets with

$p_T > 80$  GeV. The simulated data are compared with two predictions using either PYTHIA or ALPGEN.

The measurement of the inclusive jet cross section is one of the most important early measurements at the LHC. Due to the high cross section, it can be measured up to very high  $p_T$  values already at the beginning of data taking. Figure 3 shows a prediction for  $10 \text{ pb}^{-1}$  of CMS data [9], using jets with  $|\eta| < 1$ . Such measurements will allow to test perturbative QCD calculations in a new regime, place constraints on PDFs and  $\alpha_s$ , and probe signatures of new physics (e.g. quark compositeness).

ATLAS recently performed a detailed investigation [10] of the systematic errors associated with the inclusive jet cross section measurement. The dominating error is clearly due to the knowledge of the jet energy scale: An error of 5 (10) % on the jet energy scale leads to a cross section uncertainty of 35 (70) % at 1 TeV and 50 (100) % at 2 TeV. On the other hand, the statistical uncertainty (for a bin width of 100 GeV) is much smaller, namely 2 (30) % at 1 (2) TeV for an integrated luminosity of  $100 \text{ pb}^{-1}$ . The theoretical uncertainty originating from the scale uncertainty of the next-to-leading order (NLO) calculation, obtained by varying the factorization and renormalization scales  $\mu_f = \mu_r$  between  $p_T/2$  and  $2p_T$ , is estimated as 5 – 10% at 1 TeV.

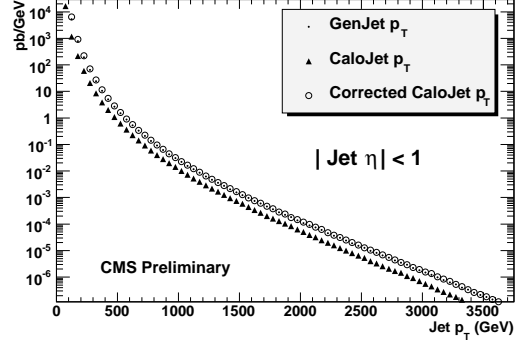
### 3. Top Quark Physics

The LHC will be a top quark factory: at 14 TeV centre-of-mass energy, around  $8\text{M}$   $t\bar{t}$  pairs will be produced per year of data taking ( $10 \text{ fb}^{-1}$ ). At LHC the  $t\bar{t}$  production is predominantly gluon induced, in contrast with the TEVATRON where top is mostly produced from (anti-) quarks in the proton, and the cross sections, both for pair production as well as for electroweak single production of top quarks, will be increased by about two orders of magnitude.

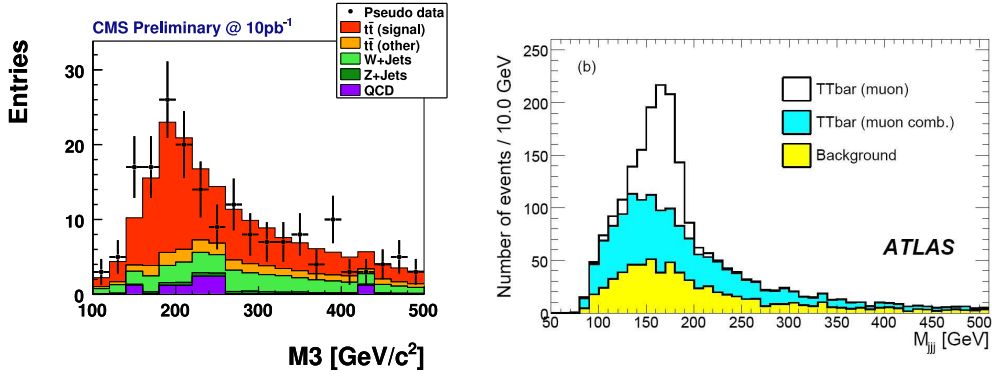
The LHC top quark physics program consists first of the rediscovery of the top quark, followed by (differential) cross section measurements, measurements of the properties of the heaviest Standard Model fermion (mass, spin etc.), as well as the search for new heavy resonances decaying into  $t\bar{t}$  pairs. Besides the fundamental interest in the top quark and its properties itself, top production constitutes one of the major backgrounds in many scenarios of new physics, such as supersymmetry. Moreover, top events are very useful for the understanding of the detector, as they involve most of the physics objects (leptons, jets, missing  $E_T$  (MET), b-tagging), and can also be used to constrain the JES and the b-tagging efficiency.

#### 3.1 $t\bar{t}$ Cross Section

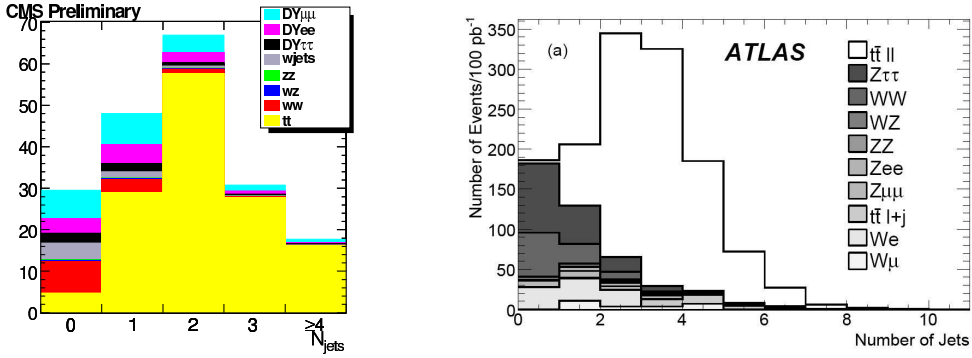
The  $t\bar{t}$  production cross section has been estimated [11] as  $\sigma(t\bar{t}) = 908 \pm 83(\text{scale}) \pm 30(\text{PDF}) \text{ pb}$  at 14 TeV and  $\sigma(t\bar{t}) = 414 \pm 40(\text{scale}) \pm 20(\text{PDF}) \text{ pb}$  at 10 TeV (using NLO calculations with next-



**Figure 3:** Inclusive jet cross section vs  $p_T$  for  $10 \text{ pb}^{-1}$  simulated data (CMS).



**Figure 4:** (left) Invariant mass of the three jets with the highest vectorially summed  $E_T$  in the semileptonic muon channel for  $10 \text{ pb}^{-1}$  (CMS). (right) The same quantity for  $100 \text{ pb}^{-1}$  (ATLAS).

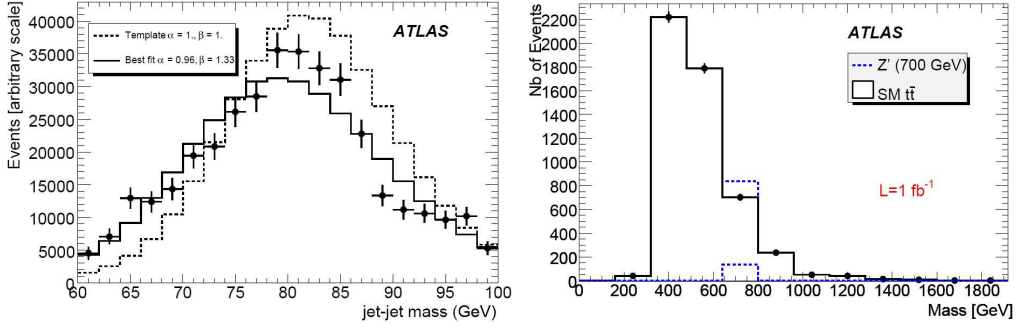


**Figure 5:** Jet multiplicity in the top dilepton channel for  $10 \text{ pb}^{-1}$  of simulated CMS data (left) and for  $100 \text{ pb}^{-1}$  of simulated ATLAS data (right).

to-leading-log (NLL) resummation,  $m_t = 171 \text{ GeV}$  and the CTEQ 6.5 PDFs). CMS has studied the rediscovery of the top quark in the semileptonic muon channel [12] with a simple selection without b-tagging or MET requirement. Requesting one isolated muon with  $p_T > 30 \text{ GeV}$  and at least 4 jets with  $p_T > 65, 40, 40, 40 \text{ GeV}$ , around 128  $t\bar{t}$  signal and 88 background (mostly W+jets) events are expected for an integrated luminosity of  $10 \text{ pb}^{-1}$ , see Figure 4 (left). ATLAS has investigated [2] the lepton+jets channel (electron or muon) for  $100 \text{ pb}^{-1}$ , requesting one lepton with  $p_T > 20 \text{ GeV}$ , at least 4 jets with  $p_T > 40, 40, 40, 20 \text{ GeV}$ ,  $\text{MET} > 20 \text{ GeV}$  and b-tagging. They expect 755 (143) signal (background) events without b-tag and 403 (42) signal (background) events when requiring at least one b-tag jet. The cross section is extracted from a fit to the invariant mass distribution, see Figure 4 (right), and the expected significance is around 9 for  $100 \text{ pb}^{-1}$ .

In the dilepton channel, where QCD background is not an issue, CMS expects [13] a statistical uncertainty on the number of  $t\bar{t}$  events of around 10% for  $L = 10 \text{ pb}^{-1}$ , combining  $ee$ ,  $\mu e$  and  $\mu\mu$  channels, see Figure 5 (left). Events are selected requesting two leptons with  $p_T > 20 \text{ GeV}$ , at least two jets with  $p_T > 30 \text{ GeV}$ , a MET cut and a Drell-Yan veto. With softer jet cuts ( $p_T > 20 \text{ GeV}$ ), ATLAS estimates [2] that the cross section can be measured in this channel with a precision of  $4(\text{stat.}) \pm 4(\text{syst.}) \pm 2(\text{PDF}) \pm 5(\text{lumi})\%$  for  $100 \text{ pb}^{-1}$  (Figure 5 right).

The expected performance of the measurement of the top quark mass is discussed in [14].



**Figure 6:** (left) Dijet invariant mass in semileptonic  $t\bar{t}$  events as used in a template fit to determine the light JES in ATLAS. (right)  $m_{t\bar{t}}$  distribution showing a  $Z'$  signal ( $m_{Z'} = 700 \text{ GeV}$ ,  $\sigma * \text{BR} = 11 \text{ pb}$ ) on top of the Standard Model  $t\bar{t}$  background (ATLAS  $1 \text{ fb}^{-1}$ ).

### 3.2 Top as Calibration Tool

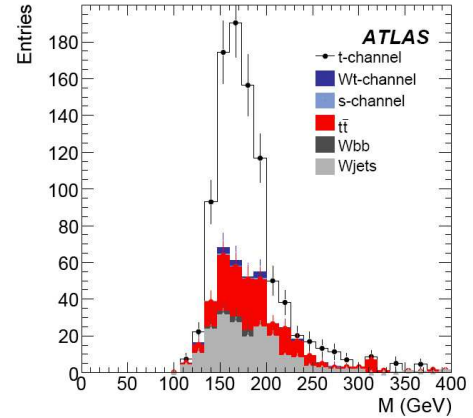
$t\bar{t}$  events are also very useful calibration candles. ATLAS has studied [2] a determination of the light jet energy scale using an  $m_W$  constraint on the invariant mass of the two light jets in semileptonic  $t\bar{t}$  events. A precision of 2% can be achieved with  $50 \text{ pb}^{-1}$  of data (Figure 6 left). A similar CMS study [15] estimates an error of 1% for  $100 \text{ pb}^{-1}$  of data. A high purity selection of  $t\bar{t}$  events can also be used to determine the b-tagging efficiency with a precision of 6% in  $1 \text{ fb}^{-1}$  of CMS data [16].

### 3.3 $t\bar{t}$ Resonances

Due to the large Yukawa coupling, there is a significant potential to discover new physics by searching for a new heavy resonances decaying into a  $t\bar{t}$  pair, which would manifest themselves as peaks or shape distortions in the  $m_{t\bar{t}}$  distribution. There are several experimental issues involved in reconstructing  $m_{t\bar{t}}$ . Due to the boost the top quark decay products are close by, which means that lepton isolation will deteriorate, and jets are merged. Furthermore the b-tagging performance will decrease due to the high track density in the jets. These issues are currently being addressed by both collaborations. Using a standard event reconstruction and selection in the lepton+jets channel, ATLAS estimates to exclude Kaluza-Klein gluon resonances up to  $M \sim 1.5 \text{ TeV}$  with  $1 \text{ fb}^{-1}$  [2]. A  $Z'$  signal with  $m_{Z'} = 700 \text{ GeV}$  and  $\sigma * \text{BR} = 11 \text{ pb}$  is shown in Figure 6 (right).

### 3.4 Single Top Production

The single top (and antitop) production cross section at 14 TeV has been estimated as  $10 / 247 / 56 \text{ pb}$  in the  $s / t / tW$  channels, respectively [17, 18]. It is thus around 1/3 of the size of the



**Figure 7:** Reconstructed top invariant mass in the single top t-channel in the ATLAS study for  $1 \text{ fb}^{-1}$ .

$t\bar{t}$  production. The main backgrounds are  $W$ +jets and  $t\bar{t}$ , which need to be controlled using data driven techniques. In the context of low signal over background ratio, the use of sophisticated tools such as genetic algorithms, likelihoods and Boosted Decision Trees will be very useful. A precise determination of the single top cross section can be achieved with a few  $\text{fb}^{-1}$  in the  $t$ - (see Figure 7) and  $Wt$ -channels. Recent ATLAS studies [2] predict a signal to background ratio of 1.3 (0.3) in the  $t$  ( $Wt$ ) channel using 1 (10)  $\text{fb}^{-1}$  of data. For the  $s$ -channel, higher statistics are needed. Previous CMS studies can be found in [19, 20].

#### 4. Conclusions

A summary of the potential of ATLAS and CMS in QCD and top quark measurements has been presented, with a special emphasis on the early data taking phase. There, the focus will be on the understanding of the detectors, and on precise measurements of known Standard Model processes, which will pave the way for searches for new physics, for which QCD jet and top quark events are the most important backgrounds. CMS and ATLAS are well prepared to achieve these goals.

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