

## CHALLENGES FOR EARLY DISCOVERY IN ATLAS AND CMS

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The challenges for a discovery of new physics with  $1 \text{ fb}^{-1}$  of LHC data for ATLAS and CMS are discussed. Four specific examples are chosen: a deviation of QCD jet distributions at high  $E_T$ , high-mass dilepton pairs, Higgs search in the WW decay channel, and low mass supersymmetry.

### 1 Introduction

The Large Hadron Collider (LHC) is a proton-proton collider with a center-of-mass energy of 14 TeV, currently under construction at CERN, Geneva. At the time of this conference <sup>a</sup>, the LHC was still planning to have an engineering run in the fall of 2007, in order to establish single beam operation at the injection energy of 450 GeV, and provide first collisions at fairly low luminosity, at 900 GeV center-of-mass energy <sup>b</sup>. The first collisions at  $\sqrt{s} = 14 \text{ TeV}$  could occur in spring 2008, and with a steadily increasing luminosity during the next 26 weeks of proton-proton running, the ATLAS and CMS experiments might collect an integrated luminosity close to  $1 \text{ fb}^{-1}$  by the end of 2008. In order to be able to present first results at Moriond 2009, ATLAS and CMS face a number of challenges, some of which will be discussed in this paper. Hereby we will focus on four examples of possible signs of new physics in first data.

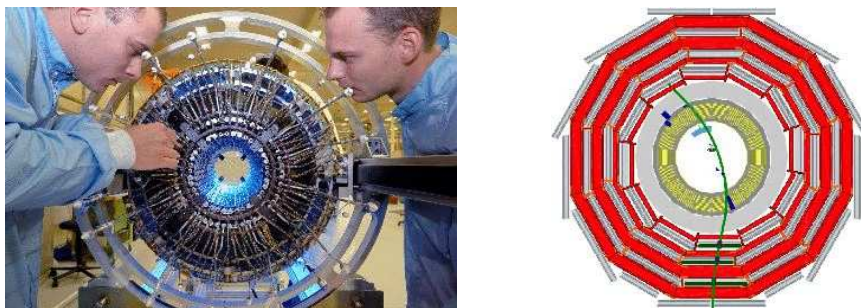


Figure 1: Left: construction of the ATLAS pixel detector. Right: a muon, from a cosmic ray shower, traversing a part of CMS. Data taken in a commissioning run end of 2006 with CMS in the surface hall.

The first challenges that ATLAS and CMS face are still severe: the completion of subdetector construction, installation and commissioning, establishing reliable detector operation, and getting the trigger, data acquisition and detector calibration infrastructure to work as designed.

<sup>a</sup>Talk given at Moriond 2007, Electroweak Interactions and Unified Theories, March 10-17, 2007

<sup>b</sup>However, delays in the schedule now make this engineering run increasingly unlikely.

The data is to be distributed and analyzed on the Grid, and this also needs to be commissioned. ATLAS is currently undergoing such a (Monte Carlo) data generation and analysis challenge, which will also lead to performance estimates that update the physics TDR (technical design report) from 1999<sup>1</sup>. CMS has produced an updated physics TDR in the summer of 2006<sup>2</sup>.

At any energy, soft (low  $p_T$ ) hadronic interactions, or “minimum bias” events, will be most common. Various Monte Carlo generators differ significantly in their predictions of the cross section and the charged particle multiplicity at  $\sqrt{s} = 14$  TeV. Since these minimum bias events set the background for trigger and reconstruction, measuring their properties will be first priority for ATLAS and CMS. Furthermore, these events are useful for tracking studies and calorimeter intercalibrations.

## 2 QCD (di)jets at high $E_T$

The large center-of-mass energy of the LHC gives access to a kinematic region of QCD jet production that has never been probed before. With  $1 \text{ fb}^{-1}$  of data, jets of 3-3.5 TeV transverse energy ( $E_T$ ), and di-jet masses of up to 6 TeV are accessible. New physics, in the form of quark substructure and excited quarks, contact interactions, or resonances, could appear, as shown in Figure 2. Two main uncertainties must be tackled before any excess can be interpreted as new physics: parton density function (pdf) uncertainties, and the jet energy scale.

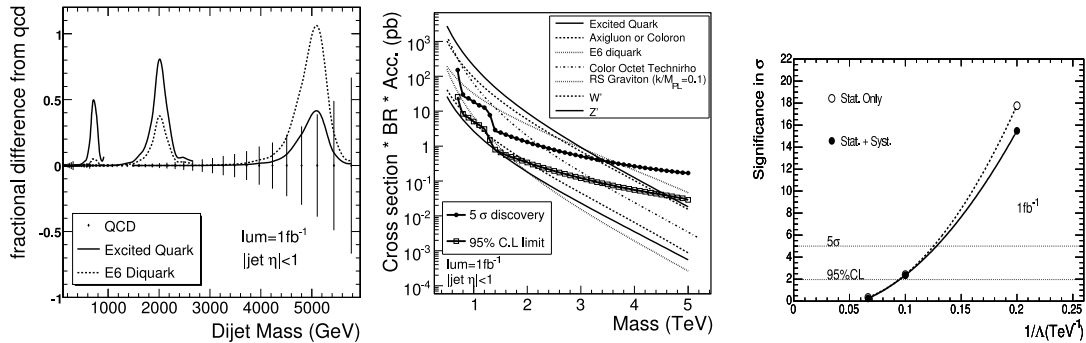


Figure 2: Left: deviations from the QCD prediction of the dijet mass distribution, for two hypothetical models of new physics, each at three different masses. The vertical bars represent the statistical error with  $1 \text{ fb}^{-1}$  of data. Center: exclusion and discovery limits on the cross section for various new particles, as a function of the particle mass. Right: significance for an exclusion or a discovery of contact interactions, for  $1 \text{ fb}^{-1}$  of data, as a function of the (inverse of the) contact interactions scale. Plots from CMS.

The pdf uncertainties arise mainly from the uncertainties on the gluon distribution function at high  $x$ . The high  $E_T$  jet data from ATLAS and CMS can in fact be used to constrain these uncertainties. In order not to sweep new physics under the rug in such a procedure, it is important to fit also complementary processes, like photon plus jet production, in pdf fits, and to measure jet production over a large kinematic range: new physics is often more central, whereas pdf effects show up over all phase space. ATLAS has shown that with  $1 \text{ fb}^{-1}$  of data, already an improvement from the current situation can be obtained, as shown in Figure 3. Beyond that, however, the systematic errors on the data must be tackled: reducing these errors help more than adding more luminosity. These systematic uncertainties concern mainly the jet energy scale.

The jet energy scale will initially be known only from test beam, cosmics and calibration systems, to not better than 5-10%. With first data, a data-driven jet energy scale determination program must be started immediately. This is a major effort. As a comparison: it has taken the D0 collaboration five years of continuous effort by a large group of people to reach now

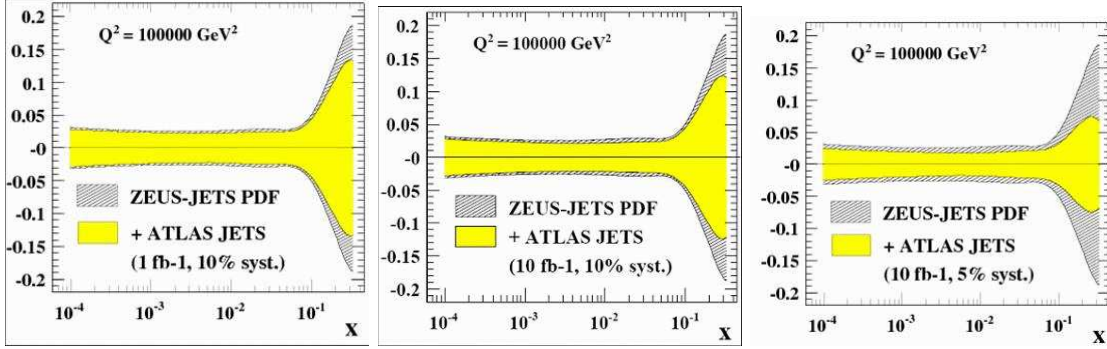


Figure 3: Uncertainty on the gluon distribution function as a function of  $x$ , for  $Q^2 = 100000 \text{ GeV}^2$ , at this moment (ZEUS-JETS PDF), and including  $1 \text{ fb}^{-1}$  (left) or  $10 \text{ fb}^{-1}$  (center) of ATLAS jets data with a 10% systematic uncertainty, and including  $10 \text{ fb}^{-1}$  (right) of ATLAS data with a 5% systematic uncertainty.

2% uncertainty on the energy scale of jets between 30 and 200 GeV. ATLAS and CMS aim for 2-3% after one year, using photon plus jets, Z plus jets, and top-quark pair events. The latter uses the W mass constraint on the two light-quark jets, the former two need a calibration of the electromagnetic energy scale first. Jets from b-quarks need a different calibration than light-quark jets.

Concerning new physics, CMS estimates a discovery potential with  $1 \text{ fb}^{-1}$  of data for excited quarks up to masses of 3.4 TeV, for diquarks in an  $E_6$  model up to 3.7 TeV, and for the scale of contact interactions up to 7.7 TeV. The sensitivity of ATLAS is expected to be similar.

### 3 High mass lepton pairs

New physics may well show up in high-mass lepton pairs. Resonances such as  $Z'$ , gravitons in the Randall-Sundrum model, or Kaluza-Klein excitations in models with universal extra dimensions may be seen in the dilepton mass distribution, on top of a Drell-Yan continuum background that falls rapidly with increasing mass. Large extra dimensions of the ADD-model type will not show up as resonances, but as deviations from the mass and angular spectrum of Drell-Yan lepton pairs.

Reconstruction of electrons and muons requires a well-calibrated and aligned detector. The alignment of the CMS and ATLAS inner detectors will be a significant task. CMS has some 20000 silicon modules, or a total of 120000 alignment parameters to be determined; ATLAS has about 6000 modules. Initially, alignment will come from survey measurements, dedicated hardware systems, and cosmic-ray muon data. The ATLAS silicon strip detector includes a system of frequency scanning interferometers, that measure the movements of whole structures (barrels, discs) very precisely over timescales of hours; the CMS inner detector has a laser calibration system. The ATLAS muon spectrometer has an extensive set of laser alignment systems. Eventually, tracks from the data will provide alignment information, but it will be a challenge to do this for all modules, with little residual systematics.

The momentum scale of muons is very much determined by the alignment accuracy of the inner detector and the muon system. It is calibrated with muon pairs from decay of resonances such as the Z boson, and  $J/\psi$  and  $\Upsilon$ . Three days of data taking at  $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  will provide a sample of more than  $10^5 Z \rightarrow \mu^+ \mu^-$  events, and eventually the muon momentum scale can be determined to better than 0.1%.

Electrons are measured both in the tracking system and in the electromagnetic calorimeter (ECAL). The CMS ECAL consists of lead tungstate crystals, and will in first instance be intercalibrated to a 0.4 to 2.0% uniformity with single electrons and minimum bias events. The

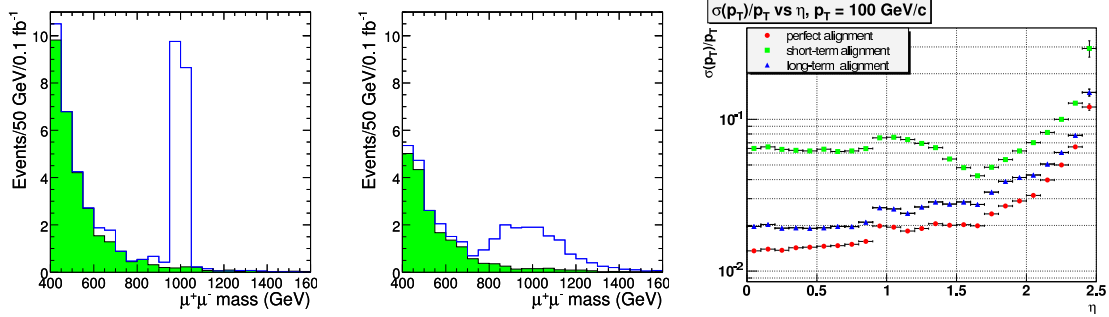


Figure 4: Muon-pair mass distribution from the decay of a 1 TeV  $Z'$ , with ideal alignment (left), or alignment as expected at LHC start-up (center) (also denoted short term alignment) in CMS. Right: track  $p_T$  resolution for a  $p_T = 100$  GeV track in CMS, as a function of pseudorapidity  $\eta$ , for ideal, short-term and long-term (more than a few  $\text{fb}^{-1}$  of data) alignment.

ATLAS ECAL is a lead and liquid argon calorimeter; the goal is a 0.4 to 1.0% uniformity. Both detectors will derive the overall energy scale from  $Z \rightarrow e^+e^-$  events to better than 0.1%.

It should be noted that the energy scale is affected by many effects (magnetic field uniformity, material in the detector, response, alignment etc), and that all these need to be disentangled. After all, the energy scale needs to be extrapolated from the Z peak to high  $p_T$ , where the new physics is expected. A careful Monte Carlo modeling is crucial.

Trigger and reconstruction efficiencies must be obtained from the data itself, and it is important to include redundant and as-little-bias-as-possible triggers in the trigger menu. Also redundant object reconstruction methods are needed: e.g. muons must be reconstructed in the inner detector, in the calorimeter, and in the muon system, so that efficiencies and fake rates can be determined.

On the theoretical side, there are still uncertainties on the Standard Model prediction, originating from missing higher orders in the calculation, scale variations, and pdf uncertainties. ATLAS and CMS will try to select control samples from data to measure the Standard Model background, but one should realize that new physics will probably show up in “untypical” corners of phase space. Therefore, good Monte Carlo predictions are still important, and some NLO calculations are still needed<sup>3</sup>.

As shown in Figure 5, a  $Z'$  could be discovered with  $1 \text{ fb}^{-1}$  up to masses of 2-2.8 TeV, depending on the  $Z'$  couplings, Randall-Sundrum graviton resonances up to 2.3 TeV, and ATLAS and CMS would be sensitive to a 6 TeV fundamental Planck scale if there would exist three large extra dimensions of the type of the ADD model (4 TeV for six extra dimensions).

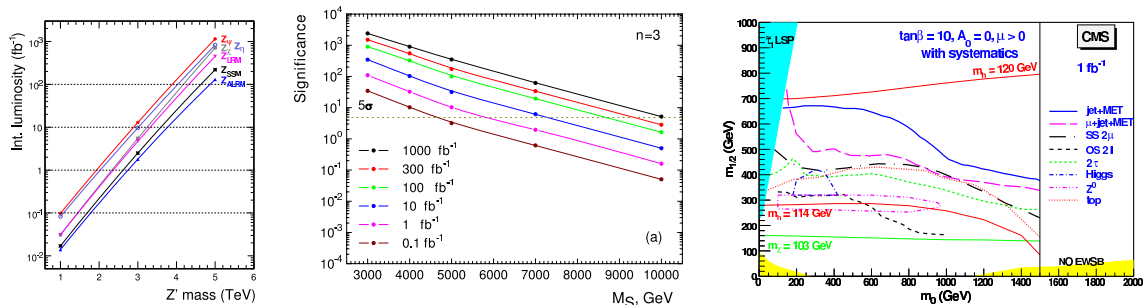


Figure 5: Left: integrated luminosity needed for a  $Z'$  discovery in CMS, as a function of  $Z'$  mass, in various models with different  $Z'$  couplings. Center: significance of a discovery of large extra dimensions in the ADD model for various luminosities, for three extra dimensions, as a function of the fundamental Planck scale  $M_S$ . Right: CMS reach in the mSUGRA parameters  $m_{1/2}$  and  $m_0$ , for  $\tan\beta = 10$ ,  $A_0 = 0$ ,  $\mu > 0$ , for  $1 \text{ fb}^{-1}$  of data.

## 4 Higgs search in the $WW \rightarrow \ell\nu\nu$ channel

One of the most promising Higgs search channels with early data is the search for a Higgs boson in the mass range 150-170 GeV. CMS estimates that a discovery can be made with less than  $1 \text{ fb}^{-1}$  of data<sup>4</sup>, and ATLAS also considers this, in particular for Higgs production through WW fusion, the most promising channel.

Since there are two neutrinos in the final state, the mass resolution is poor, and this is essentially a counting experiment. Therefore, it is extremely important to have a good understanding of the background. The major backgrounds, WW and top-quark pair production, are extracted from the data itself through a procedure involving several control samples. The uncertainties related to this procedure have been studied in detail, and seem to be under control. A small, but important, component to WW production comes from gluon-gluon fusion processes.

## 5 Supersymmetry

Supersymmetry (SUSY) is a theoretically attractive candidate for physics beyond the Standard Model, and there are several arguments in favor of supersymmetry at the TeV scale, accessible at the LHC. If the LHC does not find any evidence for supersymmetry, it is extremely unlikely that supersymmetry is the answer to open issues in the Standard Model like the hierarchy problem. Also the interpretation of the lightest supersymmetric particle as a dark matter candidate will be problematic, certainly if direct detection and astroparticle physics experiments also do not find evidence.

If the SUSY mass scale is only just above the Tevatron limits, SUSY is the prime candidate for an early discovery at the LHC. A search for SUSY in early data must be robust (able to cope with background uncertainties and a non-optimal detector) and general, yet efficient. Excellent opportunities exist in final states with high  $E_T$  jets, and significant missing transverse energy ( $\cancel{E}_T$ ). In order to suppress the QCD background and facilitate triggering, it is possible to further demand one (or more) high  $p_T$  lepton(s). Such final states typically arise in the decay chains of squarks and gluinos, which will be copiously produced at the LHC, if kinematically allowed. Assuming R-parity conservation, the lightest SUSY particle will escape the detector unseen; if R-parity is violated there will be little  $\cancel{E}_T$ , but still events with many high  $E_T$  jets. Standard Model backgrounds to the SUSY search mainly come from top quark pair production, Z or W boson production in association with jets, and QCD jet production. An example of the  $\cancel{E}_T$  distribution in signal and background is shown in Figure 6 (left).

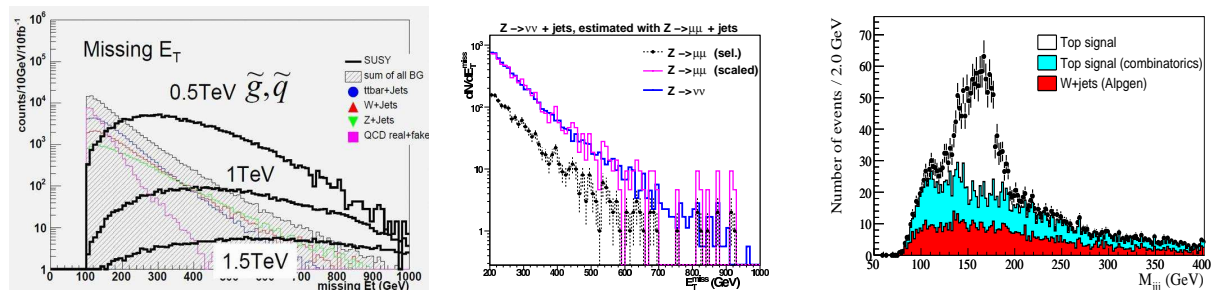


Figure 6: Left:  $\cancel{E}_T$  distribution in multi-jets final states, for potential SUSY signals at 0.5, 1.0 and 1.5 TeV mass scales, and  $\cancel{E}_T$  in various backgrounds. Center:  $\cancel{E}_T$  distribution of Z ( $\rightarrow \nu\nu$ ) plus at least two jets events, and how this background to SUSY could be estimated from Z ( $\rightarrow \mu\mu$ ) events, properly scaled. Right: Expected signal for top-quark pairs in  $100 \text{ pb}^{-1}$  of early ATLAS data, without using b-tagging. Shown is the invariant mass distribution of the three jets assigned to a hadronically decaying top quark.

There are several challenges for an early SUSY discovery: reconstruction of leptons, jets,

and  $\cancel{E}_T$  in busy events; fake  $\cancel{E}_T$  from detector effects; trying to be general, yet efficient, in the SUSY search; and understanding the Standard Model background well.

The  $\cancel{E}_T$  is a measure of energy carried away by escaping, unmeasured particles, such as neutrinos, or (semi)stable weakly interacting particles in new physics models. Measuring  $\cancel{E}_T$  relies on accurate reconstruction of the transverse momentum balance, and is affected by detector effects (holes, noise, punchthrough), and a finite resolution. QCD jets can have real  $\cancel{E}_T$  due to neutrinos, and it is a challenge to understand the high  $\cancel{E}_T$  tail well.

Reconstruction of objects in a busy environment can be tested at the LHC in top-quark pair production events, which constitute an excellent calibration sample, and also provide interesting physics. At the LHC, the ratio of production of top quark pairs and production of background to top quark pairs is more favorable than at the Tevatron, and clean samples of  $t\bar{t}$  events can be selected, in particular in events with at least one electron or muon. ATLAS, for example, expects a signal as shown in Figure 6(right) in  $100 \text{ pb}^{-1}$  of early data, even without b-tagging. Such a sample will be useful for the jet energy scale calibration, and calibration of b-tagging and  $\cancel{E}_T$ . With a working b-tagging, very clean  $t\bar{t}$  samples can be selected.

The estimation of backgrounds in SUSY searches is performed as much as possible from data. As an example (Figure 6(center)) the important Z ( $\rightarrow \nu\nu$ ) plus jets background in the SUSY jets plus  $\cancel{E}_T$  channel can be calibrated with a clean Z ( $\rightarrow \mu\mu$ ) plus jets sample, but also with W ( $\rightarrow \mu\nu$ ) plus jets samples. Many other control samples are under study.

## 6 Final comments

The first LHC data is eagerly awaited by a large community of experimentalists and theorists. There will be a strong pressure on the experiments to provide results early, and it is hard to prevent high-profile analyses to take place in a “glass box”. There will also be strong internal competition within ATLAS and CMS, and between ATLAS and CMS. It is important not to compromise on the quality of the results, after all the LHC will be operating in new territory. In this sense, the issue of blind analyses at the LHC, in order to prevent any bias, has come up, but has also raised internal discussions (at least in ATLAS) on the feasibility.

ATLAS and CMS are learning more and more from CDF and D0, not the least since many CDF and D0 physicists are joining ATLAS and CMS. There is still a lot to be learned from the Tevatron in terms of analysis techniques and background estimations from data, and on W and Z production. Certainly, CDF and D0 have shown that understanding the detector with data will be a major challenge.

## References

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