Standard Model Physics with ATLAS and CMS

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The study of Standard Model (SM) physics is crucial at the LHC for several reasons. Before any discovery can be claimed a detailed understanding of the detectors should be reached and benchmark SM processes should be measured. A precise measurement of the various parameters is needed as a consistency check of the SM. Moreover, SM processes can be directly sensitive to new physics, they will allow to test QCD predictions and measure PDFs and are backgrounds for many new physics channels. In this report, the status of some analysis at ATLAS and CMS is reported focusing on W and Z inclusive cross sections and on W and top quark mass measurements. Expected results on early data are also shown.

1 Introduction

The Large Hadron Collider (LHC) is a proton proton collider designed to provide collisions at a center of mass energy of 14 TeV with a nominal luminosity of 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The LHC was built at CERN as a discovery machine with the target to find the Higgs Boson and any possible evidence of new physics beyond the Standard Model (SM). Two general purpose experiments (ATLAS [1] and CMS [2]) have been constructed to study the collisions provided by the LHC. They are currently in the final commissioning phase [3,4] and are ready to collect data.

Before any discovery can be claimed a set of key issues should be addressed by the experiments: the detectors response should be understood in detail and SM processes (W,Z,t) should be accurately measured as they can be considered as benchmark processes to assess the comprehension of the measurements.

The LHC can provide stringent tests of the Standard Model consistency measuring several fundamental parameters. A non exhaustive list includes the W boson mass and width (M_W and Γ_W through the W boson decay distributions), the top quark mass m_t and $\sin^2\theta_W$ via the Z forward-backward asymmetry. In addition to that, some processes (e.g. rare top decays) have a direct sensitivity to new physics. Cross sections which are known theoretically with high accuracy (as those of the vector bosons) are crucial to test QCD predictions in an unexplored regime and to measure Parton Density Functions (PDFs). Moreover, SM processes should be carefully studied at the LHC because they are a background to many new physics channels.

At the time of writing these proceedings, April 2009, it is foreseen to have the first proton-proton collisions before the end of the year. It is planned to run without long intervals during the winter with the goal to integrate $\sim$200 pb^{-1}. The energy per beam will be of 450 GeV at the beginning and will rise up to 5 TeV.

In this paper, the expected results for some measurements of SM processes at the LHC are presented to show the status of the analyses and the expected performance. More details and

the description of the analyses not shown here can be found in [6,7] and in the references cited in the text. The studies are based on detailed simulations of the physics processes and of the detectors. The inclusive Z and W cross sections measurements are discussed in section 2; the measurement of the W mass is described in section 3 and the top quark pair production cross section and top mass measurements are presented in section 4.

2 Inclusive W and Z cross sections measurements.

The study of the production of W and Z events at the LHC is fundamental in several respects. First, the calculation of higher order corrections is very advanced, with a small theoretical uncertainty (<1%). Such precision makes W and Z production a stringent test of QCD.

Z and W production cross sections are expected to be very large. For a center of mass energy of 10 TeV (14 TeV) we will have $\sigma_{W\to l\nu}$=14.3 nb (20.5 nb) and $\sigma_{Z\to ll}$=1.35 nb (2.02 nb); the calculations are at NLO accuracy. The experimental signatures for these processes are very clean (in particular Z→ ll). Thus, they will be extensively used as *standard candles* processes for understanding the experiments and tuning the Montecarlo, providing calibration and alignment of the detectors; setting the energy scales and resolutions and measuring the efficiencies for leptons.

Finally, the clean and fully reconstructed leptonic final states, in Z events, will allow a precise measurement of the transverse momentum and rapidity distributions. These distributions will constrain non perturbative QCD aspects and the PDFs. The high expected statistics will bring significant improvement on all these aspects, and this improvement translates to virtually all physics at the LHC, where strong interaction and PDF uncertainties are a common factor.

The selection of Z→ $\mu\mu$ events (the CMS analysis [8] is presented) starts requiring one single muon at the trigger level. Two high p_T muons (p_T>20.0 GeV) with opposite charge sign should be reconstructed and should be isolated ($\sum p_T$<3 GeV for all the other tracks in a cone ΔR<0.3).

In the case of Z→ee (ATLAS analysis [6] is discussed), the trigger requires one electron with p_T>10 GeV. Two clusters in the Electromagnetic Calorimeter (E_T>15 GeV) are then required at reconstruction stage; they should be isolated ($\sum E_T/{E_T}^e$<0.2 in a cone ΔR<0.45, where the electron energy is excluded in $\sum E_T$). These analyses are based on robust cuts in order to be safe against harsh experimental conditions; for example a common vertex is not required nor a cut based on the tracks impact parameter.

The background estimation can be performed from the sidebands and/or from simultaneous fit to signal and background. Anyway this is a low background sample, in particular in the muon case. The results of the selections are shown in figure 1 for the case Z→ $\mu\mu$ channel.

The selection of W→$e\nu$ events (CMS cuts [9] are reported) starts requiring a single isolated electron at trigger level. A high E_T electron (E_T>30 GeV) should be reconstructed; it is required to be isolated in the tracker (no tracks with p_T >1.5 GeV, except for the one of the electron, within a cone ΔR<0.6), in the electromagnetic calorimeter ($\sum E_T/E_T^e$ <0.02; ΔR<0.3) and in the hadronic calorimeter ($\sum E_T/E_T^e$ <0.10; 0.15<ΔR<0.3). Events with a second electron having E_T >20 GeV are rejected.

W→ $\mu\nu$ events are obtained (in the ATLAS analysis [6]) with one muon having p_T>20 GeV at the trigger level. A high p_T muon (p_T>25 GeV) should be reconstructed and must be isolated (the energy deposited in the calorimeter around the muon track in a cone ΔR<0.4 should be lower than 5 GeV). Cuts on E_T^{Miss}>25 GeV and M_{TW}>40 GeV are also applied.

In the electron final state the dominant background are jet final state events. To determine the shape of the background two method are foreseen; CMS propose to use a data sample passing electron selection with isolation criteria inverted while ATLAS exploits a γ+jet sample obtained using the same selection as for the signal but requiring no matching tracks in the Inner Detector.

In the muon final state the background comes from Z→ $\mu\mu$ and W→ $\tau\nu$ events. As these

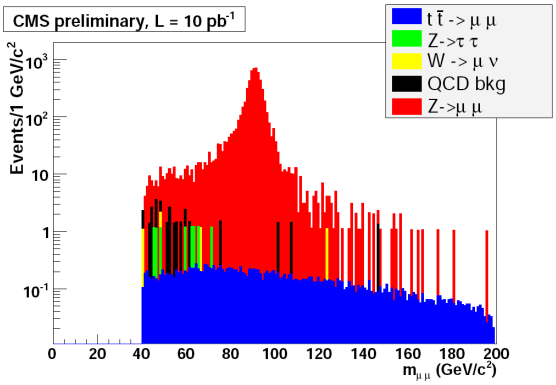

Figure 1: Invariant mass distributions for Z→ $\mu\mu$ as expected in CMS for an integrated luminosity of 10 pb^{-1} .

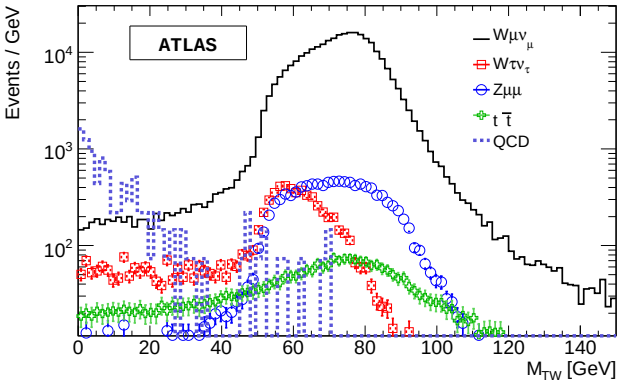

Figure 2: Transverse mass distribution for W→ $\mu\nu$ events as expected in ATLAS for an integrated luminosity of 50 pb^{-1} before the cut on M_{TW} described in the text.

processes are well understood, the shape of the background will be obtained from Montecarlo. In figure 2 the transverse mass distribution is shown for the case W→ $\mu\nu$.

$$\sigma_{W(Z)} = \frac{N^{obs}_{W(Z)} - B_{W(Z)}}{\epsilon_{W(Z)} \cdot A_{W(Z)} \cdot \int Ldt} \quad ; \quad \frac{d\sigma_{W(Z)}}{\sigma} = \frac{dN \oplus dB}{N - B} \oplus \frac{d\epsilon}{\epsilon} \oplus \frac{dA}{A} \oplus \frac{dL}{L} \tag{1}$$

The cross sections and the relative errors are computed as in eq. 1. $N^{obs}_{W(Z)}$ is the number of selected events; $B_{W(Z)}$ is the estimated number of background events, $\epsilon_{W(Z)}$ and $A_{W(Z)}$ are respectively the trigger and reconstruction efficiency and the acceptance and $\int Ldt$ is the integrated luminosity. The efficiencies will be computed from data using the Tag and Probe technique while the acceptance will be computed using the Montecarlo. At the beginning the dominant uncertainty (∼10%) will come from luminosity measurements. This number will be reduced with a better knowledge of the machine and when ALFA [5] will come into play.

The expected uncertainties on the measured cross sections are presented for different values of the integrated luminosity in table 1. The error on the luminosity is not taken into account. The uncertainty on identification and reconstruction efficiencies are expected to be at the level of 1% (3%) in the electron (muon) channel in the initial phase and to go well below 1% on a longer time scale after an integrated luminosity of 1 fb^{-1} will be collected. The uncertainty on the background is foreseen to be at the level of 5% (<1%) in the electron (muon) channels at the beginning; they will be reduced with more stringent selections when the available statistics increases.

Table 1: Expected uncertainties on the measured cross sections; the error on the luminosity is not considered.

Experiment	Process	$\int Ldt$	$\Delta\sigma/\sigma$ (%)
CMS	pp→Z+X→$ee + X$	10 pb^{-1}	1.9 (stat) ± 2.3 (syst)
	pp→W+X→$e + X$		1.2 (stat) ± 5 (syst)
ATLAS	pp→Z+X→ $\mu\mu + X$	50 pb^{-1}	0.8 (stat) ± 3.8 (syst)
	pp→W+X→ $\mu + X$		0.2 (stat) ± 3.1 (syst)
CMS	pp→Z+X→ $\mu\mu + X$	1 fb^{-1}	0.13 (stat) ± 2.3 (syst)
	pp→W+X→ $\mu + X$		0.04 (stat) ± 3.3 (syst)
ATLAS	pp→Z+X→$ee + X$		0.20 (stat) ± 2.4 (syst)
	pp→W+X→$e + X$		0.04 (stat) ± 2.5 (syst)

3 W mass measurement.

The W mass (M_W) is a fundamental parameter of the SM. It is related to the mass of the top quark and the mass of the Higgs boson and needs to be measured with highest precision. The LHC aims at improving the current world average (M_W=80399±25 MeV); the W production cross section is 10 times larger than at Tevatron and the luminosity is higher. W candidate events are selected as described in the previous section. The W mass can be extracted from the distribution of one of the two observables that are most sensitive to M_W: the transverse momentum of the lepton (p_T^l) and the transverse mass of the lepton-neutrino system (M_{TW}). The value of M_W is obtained fitting the measured distributions with template distributions. The two analyses are complementary and are affected by different systematic effects. The shape of the p_T^l distribution is distorted by the transverse momentum of the W while M_{TW} is mainly affected by the finite resolution of the detectors. Z events are crucial in this analysis to build the templates and to properly account for experimental quantities like the lepton energy scale, the energy resolution and the reconstruction efficiency. There are several approaches to generate the templates. In the ATLAS analysis, the distributions are generated with the Montecarlo and then are convoluted with the momentum scales, resolutions and missing E_T response measured in Z events. The CMS collaborations uses two methods. The scaled observable method uses templates obtained by transformation of the distributions of p_T^l or of the Z transverse mass into the corresponding quantities for the W. The other method is a kinematic transformation on a event by event basis (Morphing Method): the lepton momentum in Z rest-frame is rescaled taking into account the ratio M_W/M_Z, one lepton is removed to simulate the neutrino and the observable is boosted back to detector frame.

The ATLAS collaboration studied the result of the analysis also in the case of a limited statistics; this is intended as a study to set the method and to understand what can be done with very early data. The results are listed in table 2 for the different channels and observables.

Table 2: Expected uncertainties on the W mass for 15 pb^{-1} of data.

	p_T^e	p_T^μ	$M_{TW}(e)$	$M_{TW}(\mu)$
Statistical (MeV)	120	106	61	57
Experimental (MeV)	114	114	230	230
Theo (PDF) (MeV)	25	25	25	25
TOTAL (MeV)	167	158	239	238

When the statistics will increase the measurement will become competitive. The CMS analysis performed with 1 fb^{-1} of data, for example in with the Morphing Method applied to the muon channel, results in a value of ΔM_W=40 (stat) ± 64 (syst.exp) ± 20 (syst.theo) MeV. The experimental error is dominated by the missing transverse energy scale and resolution while the theoretical uncertainty is mostly related to the uncertainties in the PDFs. It has been estimated that the systematic uncertainties can be further improved with increasing statistics; the expected result for 10 fb^{-1} is ΔM_W=15 (stat) ± 30 (syst.exp) ± 10 (syst.theo) MeV.

4 Top Quark observation and mass measurement.

The top quark has been discovered at Tevatron and their current value for the top quark mass is M_t=173.1±0.6 (stat.)±1.1 (syst.) GeV [11]. A more precise measurement of M_t is needed for consistency checks of the Standard model and to constrain the Higgs mass. The LHC offers a great opportunity to this extent because top quark pair production cross section, mainly via

gluon-gluon fusion, is of 833 pb (at NLO for $\sqrt{s}$=14 TeV), two order of magnitudes larger then at Tevatron. This measurement will be soon limited by systematic effects.

The golden channel is the lepton+jets channel in which the W from t ($\bar{t}$) quark decays leptonically and the W from the $\bar{t}$ (t) quark decays in 2 jets: $t\bar{t} \rightarrow Wb+W\bar{b} \rightarrow (l\nu)b+(jj)\bar{b}$. This channel can be selected with good purity (the isolated lepton is exploited for triggering); the hadronic side is used to measure the top mass. The dominant background are W/Z+jets events. Other background are $t\bar{t}$ in other channels and single top events. Multi-jet background (with fake leptons and missing E_T) has a very large cross section and a tiny efficiency to the selection cuts; the simulation is difficult and data driven methods are needed to estimate this contribution. In any case, this is expected to be lower than W+jets.

The study of $t\bar{t}$ events require the reconstruction of many relevant experimental signatures (e, μ, jet, missing E_T, b-jet). Therefore the observation of the top signal will be a milestone in physics commissioning of the detectors. As an example, the expectations obtained by CMS [12] on the observation of the top signal with 10 pb^{-1} is presented. The muon plus jets channel is selected requiring a muon with p_T>30 GeV isolated in the calorimeters (the energy deposit in the calorimeter excluding the muon should be lower than 1 GeV) and in the tracker (dR_{min}>0.3). At least 4 jets are required, three with E_T>40 GeV and one with E_T>65 GeV. The cut on the number of jets highly reduces the QCD and W/Z+jets background. No b-tagging of the jet is used. For 10 pb^{-1} this results in a signal to background ratio of 128/90. The overall selection efficiency (including the acceptance) is 10.3%. The shape of the W/Z+jets background is obtained from simulation and the normalization will come by comparison with a control sample at low jet multiplicities. The resulting invariant mass distribution of the three jets with the highest summed transverse energy is shown in figure 3.

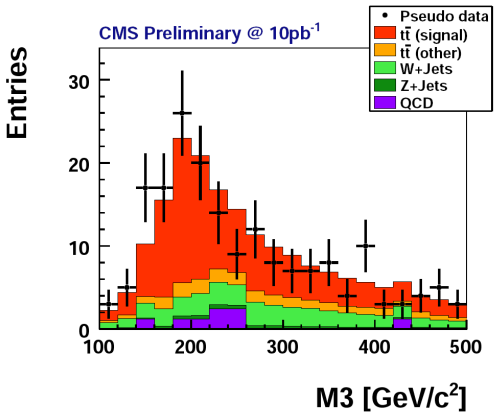

Figure 3: Invariant mass distributions of the three jets with the highest summed transverse energy as expected in CMS.

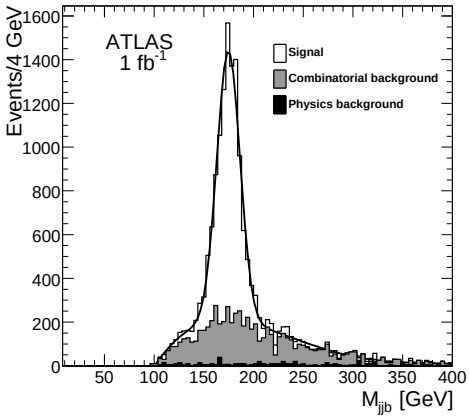

Figure 4: Invariant mass distributions of the three jets associated to the top quark as expected in ATLAS.

For more and more data being recorded and for improved understanding of the reconstruction performance, more refined analyses have been prepared; an example from ATLAS [6] is described in the following. The selection is based on one isolated lepton with p_T>20(25) GeV in the case of muons (electrons). A cut on E_T^{Miss}>20 GeV reduces the multi-jet background while a cut on at least 4 jets with p_T>40 GeV rejects W/Z+jets events. Two of the jets are required to be tagged as b-jets.

The Jet Energy Scale (JES) is the main source of systematic uncertainties. Its effect is reduced by rescaling with a minimization procedure. All possible light jet combinations are tried with a correction to their energy scale. The mass of a couple is constrained to the W mass; the pair with the best χ^2 is taken. To measure the top mass, the b-jet closest to the chosen pair

is used. The invariant mass distribution of the three jets is shown in figure 4 for an integrated luminosity of 1 fb^{-1}. The effect of the light jet energy scale (reduced with the rescaling) is of 0.2 GeV/%. The JES is expected to be known with a precision of 1% with 1 fb^{-1} of data. The uncertainty in the b-jet energy scale produces a larger uncertainty of 0.7 GeV/%; it will be initially derived from the light JES using the Montecarlo and then complemented with Z+(b-jets) data. The expected uncertainty on M_t with 1 fb^{-1} is of ΔM_t=0.3 GeV (stat.)$\pm$1 GeV (syst.).

5 Conclusions

The LHC will start providing collisions late October this year. The first steps will be understanding the detector response and establishing SM signatures. A strategy for the measurement of W and Z cross sections has been developed also for early data; simple and robust selections for electrons and muons have been set up to cope with the imperfections in calibration and alignment of the detectors. The measurement of the W and top quark mass require a detailed detector understanding and will come at a later stage. The Tag and Probe technique (applied on Z events) will provide the selection, reconstruction and trigger efficiencies directly from the data. Some methods to estimate QCD backgrounds from data were developed. On a longer scale, for the precise measurement of SM parameters, the understanding of systematics is crucial.

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