Early Electroweak and Top Quark Physics with CMS

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The Large Hadron Collider is an ideal place for precision measurements of the properties of the electroweak gauge bosons $W^\pm, Z^0$, as well as of the top quark. In this article, a few highlights of the prospects for performing such measurements with the CMS detector are summarized, with an emphasis on the first few 1/fb of data.

1 Introduction

At the Large Hadron Collider (LHC), $W^\pm$ and Z^0 bosons as well as top quarks will be produced copiously, due to the large center-of-mass energy of 14 TeV (which leads to increased production cross sections with respect to e.g. the TEVATRON) as well as the high luminosity of up to 10^{34} cm^{-2}s^{-1}. These samples can be used not only for precision measurements of standard model parameters such as m_W and m_t, but also for detector commissioning, alignment and calibration. Furthermore, standard model processes involving $W^\pm, Z^0$ bosons and top quarks constitute the primary sources of background in many Higgs boson and new physics searches.

This article [1] summarizes a few highlights of recent studies [2] of the potential of the CMS experiment regarding top quark and electroweak physics, in particular in view of the first few 1/fb of data. They have been performed with a full detector simulation, are based on the reconstruction software and calibration procedures demonstrated in [3], and include estimates of the main systematic uncertainties.

2 Electroweak Physics

The reactions $pp \to W + X$ and $pp \to Z + X$, with subsequent leptonic decays of the $W^\pm$ and Z^0 bosons, have a large cross section and are theoretically well understood. Cross sections above 10 nb (1 nb) are expected at the LHC for the $W \to l + \nu$ ($Z \to l^+ + l^-$) channel in the fiducial region of the CMS detector. Thousands of leptonic $W^\pm$ and Z^0 decays will be recorded for luminosities as low as 1 pb^{-1}. Hence, they are useful for many purposes, including a precise luminosity monitor, a high-statistics detector calibration and alignment tool and to demonstrate the performance of the CMS experiment. These reactions will be among the first to be measured at the LHC.

The measurement of the inclusive production of $W^\pm$ and Z^0 bosons with CMS has been studied in [4] and [5] for the muon and electron decay channel, respectively. The emphasis has been put on a start-up oriented event selection with high purity. Already for an integrated luminosity of 1 fb^{-1}, the uncertainty in the measured cross section will be dominated by systematics. In case of the muon channel,

$$\Delta\sigma/\sigma(pp \to Z + X \to \mu\mu + X) = 0.13 \text{ (stat.)} \pm 2.3 \text{ (syst.)} \%$$
$$\Delta\sigma/\sigma(pp \to W + X \to \mu\nu + X) = 0.04 \text{ (stat.)} \pm 3.3 \text{ (syst.)} \% \,,$$
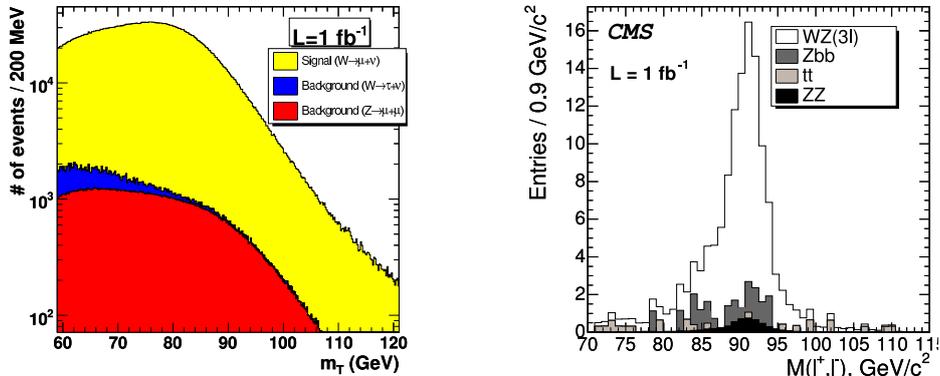
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Figure 1: (left) Transverse mass distribution in the $W \to \mu\nu$ channel for 1 fb^{-1}. (right) Dilepton invariant mass distribution in the $WZ \to 3l$ channel for 1 fb^{-1}.

where the systematic error is dominated by a 2% uncertainty originating from the modeling of the boson p_T dependence, which enters in the acceptance determination. Another important source of theoretical uncertainty is the imperfect knowledge of the parton density functions (PDFs), which affects the absolute normalization by $5 - 7\%$ [4]. Unless more precise PDF sets become available, this will be a limiting factor in comparisons between experiment and theory and in luminosity measurements via W, Z counting. But the argument can also be turned around: These processes can yield important PDF constraints, even without very precise knowledge of the luminosity, in particular by measuring the shapes of differential lepton distributions [6].

The $W^{\pm}$ boson mass is an important Standard Model (SM) parameter. CMS has investigated the use of methods involving W/Z ratios in the mass measurement, which have the advantage that many experimental and theoretical uncertainties cancel [7]. Figure 1(left) shows the simulated transverse mass distribution for 1 fb^{-1} in the muon channel [8]. For both electron and muon channel, the statistical error on m_W is estimated as 40 (15) MeV for 1 (10) fb^{-1}. The total experimental uncertainty is estimated as 40 (20) and 64 (30) MeV for the electron and muon channel, respectively. Apart from the PDF uncertainty, the dominating theoretical uncertainty originates from the modeling of the lepton p_T distribution (estimated as 30 MeV), which may be improved with higher-order calculations. Combining electron and muon channel, the uncertainty on m_W may be reduced to 10 (stat.) $\pm$ 20 (syst.) for 10 fb^{-1}.

The production of diboson pairs can be used to probe triple gauge boson couplings and thus the non-abelian gauge symmetry of electroweak interactions. Such processes are also sensitive to new physics. At the LHC the production cross sections for WZ and ZZ pairs are large (50 and 20 pb respectively). CMS has studied the production of WZ (e or μ channels) as well as of ZZ (4e channel) pairs [9]. For 1 fb^{-1}, 97 events are expected in the WZ channel (Fig. 1(right)), and a 5σ discovery is possible with just 150 pb^{-1} of data. In the $ZZ \to 4e$ channel, 71 events are expected for 10 fb^{-1}. The large signal over background (S/B) ratio makes these measurements very useful to assess the background in the search for the Higgs boson.
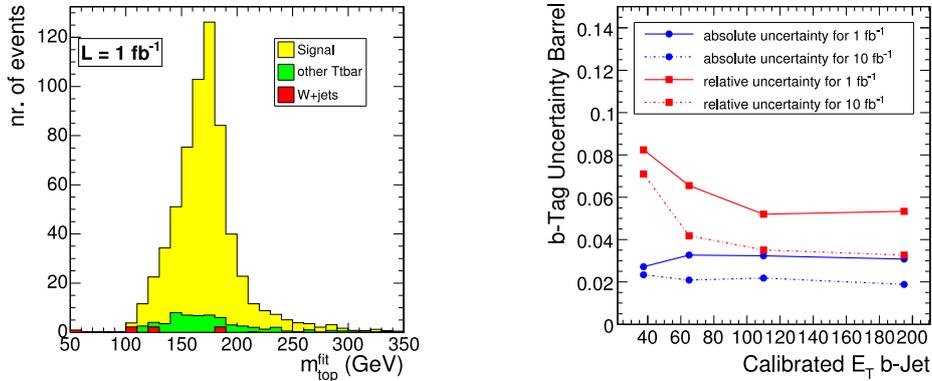
Figure 2: (left) Reconstructed m_t distribution in the semileptonic channel for 1 fb^{-1}. (right) b-tagging uncertainty in the barrel detector as a function of jet p_T, determined from $t\bar{t}$ events.

3 Top Quark Physics

The $t\bar{t}$ production cross section at the LHC is ~ 830 pb (e.g. [10]), which is more than two orders of magnitude higher than at the TEVATRON. At a luminosity of $2 * 10^{33}$ cm^{-2}s^{-1}, about 1 $t\bar{t}$ pair will be produced per second, predominantly gluon-induced. Also the cross section of the electroweak production of single top quarks is large, ~ 245 pb in the t-channel. In 1 fb^{-1} of data, around 800K $t\bar{t}$ pairs and 350K single top quarks will be produced, which makes the LHC experiments ideal laboratories to precisely measure top quark properties. In addition, since large samples of $t\bar{t}$ events will be available already with the first year's data, they can also be used as a detector commissioning tool, e.g. to study lepton identification and isolation, jet and missing E_T energy scales and b-tagging performance. The initial goal will be to measure the $t\bar{t}$ cross section, followed by the mass measurement and studies of single top production, polarization or search for flavor-changing neutral currents (FCNC).

The measurement of the $t\bar{t}$ cross section has been studied in all three decay modes [11, 12]. In the semileptonic channel (Fig. 2(left)), the cross section can be determined from event counting due to the high $S/B \sim 27$. For 1 (10) fb^{-1}, the statistical and systematic uncertainties are estimated as 1.2 (0.4) and 9.2% respectively, where the systematic uncertainty is dominated by the knowledge of the b-tagging efficiency, which is conservatively estimated as 7%. If it could be reduced to 2%, the total error on $\sigma(t\bar{t})$ could be reduced to 7% at 10 fb^{-1}, which would already constrain m_t indirectly to $\Delta m_t \sim 2 - 3$ GeV, comparable to the precision of the direct measurements at the TEVATRON. For the dilepton and fully hadronic channels, the statistical (systematic) uncertainties are estimated as 0.9 (11)% and 3 (20)% respectively at 10 fb^{-1}.

The top quark mass m_t is related to the Higgs mass via loop corrections. Also the measurement of m_t has been studied in all decay modes. In the semileptonic channel [13], a simple gaussian fit is compared with the more sophisticated *ideogram* method. For 10 fb^{-1}, a precision of $\Delta m_t = 0.21$ (stat.) ± 1.13 (syst.) GeV is estimated for this method. Thus, a 1 GeV uncertainty on m_t looks achievable, but requires a very good detector understanding. The other decay modes [12] have been investigated as well. In the dilepton channel an uncertainty of $\Delta m_t = 1.5$ (0.5) (stat.) ± 2.9 (1.1) (syst.) GeV is estimated for 1(10) fb^{-1},

where the systematic error is dominated by the jet energy scale uncertainty. In the fully hadronic channel, where a jet pairing likelihood is applied to improve the S/B from 1/9 to 1/3 at constant efficiency, the estimate is $\Delta m_t = 0.6$ (stat.) ± 4.2 (syst.) GeV for 1 fb^{-1}.

Due to the large cross section $t\bar{t}$ events are useful as a tool to commission and calibrate the detector. For instance, a study has shown that the light quark jet energy scale can be constrained to the level of 3% by applying a m_W constraint in $t\bar{t}$ events [14]. Furthermore, a high purity selection of dilepton $t\bar{t}$ events can be used to constrain the relative b-tagging efficiency (Fig. 2(right)) to 6 (4)% with 1 (10) fb^{-1} of data, as demonstrated in [15].

The electroweak production of single top quarks has been studied in [16, 17]. Single top production is a process is sensitive to new physics (e.g. heavy W' bosons, FCNC or charged Higgs bosons), but also provides a direct handle on the $|V_{tb}|$ CKM matrix element. In the t-channel, which has the biggest cross section, 2400 events are selected with an optimized selection (S/B ~ 1.3), which allows the cross section to be determined with an accuracy of $\Delta\sigma/\sigma \sim 2.7$ (stat.) ± 8.1(syst.) % for 10 fb^{-1} of data. The s- and tW-channels have been investigated as well. There, the estimated uncertainties are larger.

4   Conclusions

Due to the large cross sections, the CMS experiment will be able to make important measurements of $W^\pm, Z^0$ boson and top quark production already with the first LHC data. These measurements not only constrain standard model parameters and determine backgrounds to many new physics signals, but are also very useful as detector commissioning tools and calibration candles.

References

[1] Slides:
http://indico.cern.ch/contributionDisplay.py?contribId=113&sessionId=9&confId=9499

[2] CMS Collaboration, "Physics Technical Design Report, Vol. II: Physics Performance", J. Phys. G: Nucl. Part. Phys. **34** (2007) 995-1579.

[3] CMS Collaboration, "Physics Technical Design Report, Vol. I: Detector Performance and Software", CERN/LHCC **2006-001** (2006).

[4] J. Alcaraz, CMS Note **2006/082** (2006).

[5] G. Dissertori *et al.*, CMS Note **2006/124** (2006).

[6] A. Tricoli, A. Cooper-Sarkar and C. Gwenlan, "Uncertainties on W and Z production at the LHC", in proceedings of HERA-LHC workshop, CERN **2005-014** (2005). [hep-ex/0509002]

[7] W. Giele and S. Keller, Phys. Rev. **D57** 4433 (1998). [hep-ph/9704419]

[8] V. Buge *et al.*, CMS Note **2006/061** (2006).

[9] V. Brigljevic *et al.*, CMS Note **2006/108** (2006).

[10] N. Kidonakis and R. Vogt., Phys. Rev. **D68** 114014 (2003).

[11] J. D'Hondt, J. Heyninck and S. Lowette, CMS Note **2006/064** (2006).

[12] M. Davids *et al.*, CMS Note **2006/077** (2006).

[13] J. D'Hondt, J. Heyninck and S. Lowette, CMS Note **2006/066** (2006).

[14] J. D'Hondt *et al.*, CMS Note **2006/025** (2006).

[15] S. Lowette *et al.*, CMS Note **2006/013** (2006).

[16] V. Abramov *et al.*, CMS Note **2006/084** (2006).

[17] P. Yeh *et al.*, CMS Note **2006/086** (2006).