Top quark physics with ATLAS & CMS

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Abstract.
The potential of the ATLAS and CMS experiments for studying top quark physics at the LHC is reviewed. The measurements of the $t\bar{t}$ production cross section and spin correlations, the top quark mass, its electric charge, the structure of the Wtb vertex and the measurement of the W boson helicities, the sensitivity to anomalous couplings, top quark rare decays through Flavour Changing Neutral Currents and the single top quark production are discussed. The results shown use the full Monte Carlo simulation of ATLAS and CMS and assume a center of mass energy of 14 TeV at the LHC. Integrated luminosities in the range between $\mathscr{O}(10\ \text{pb}^{-1})$ and $\mathscr{O}(10\ \text{fb}^{-1})$ are considered, depending on the physics observables under study.

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Introduction

The top quark was discovered at FERMILAB in 1995 by the CDF [1] and D0 [2] experiments. With the start of operation of the Large Hadron Collider (LHC), top quark physics will enter a new era of precision measurements. Within the Standard Model the top quark has spin $1/2$, is the weak isospin partner of the b-quark and has charge $+2/3$. Although theory cannot predict the top quark mass, indirect evidence from electroweak precision data pointed to a high value ($m_t = 179^{+12}_{-9}$ GeV [3]), well within the range of the world average directly measured $m_t = 173.1 \pm 1.3$ GeV [4]. The mass is the only property of the top quark measured with such precision (0.8%). Due to a Cabibbo-Kobayashi-Maskawa matrix element (CKM) V_{tb} close to one, the top quark decays dominantly to a b-quark and a W boson. The on-shell decay width is $\Gamma(t \to bW)/|V_{tb}|^2 \sim 1.42$ GeV at $m_t = 175$ GeV and is known from theory with a precision better than 1% [5]. The large top quark width translates into a short lifetime $\tau_t = 1/\Gamma \sim 10^{-25}$ s, shorter than the typical hadronization time scale ($\sim 10^{-24}$ s). This implies that the top quark decays before hadronization can take place and its spin information is transferred to the decay products. This allows the study of $t\bar{t}$ spin correlations at production. Top quarks can be produced at the LHC via strong interactions in pairs ($t\bar{t}$ production) or singly through electroweak processes. Both ATLAS [6] and CMS [7] have developed research programs to prepare for the measurements of top quark physics at the LHC. In this paper the prospects for top quark physics at ATLAS and CMS are reviewed, assuming pp collisions at LHC at a center of mass energy of 14 TeV and integrated luminosities ranging from $\mathscr{O}(10\ \text{pb}^{-1})$ to $\mathscr{O}(10\ \text{fb}^{-1})$. The top quark production cross sections, the mass, the electric charge, the decay vertex structure, the anomalous couplings, the rare decays through Flavour Changing Neutral Currents (FCNC) and $t\bar{t}$ resonances are discussed. The projections presented correspond to the most up to date studies available from ATLAS [8] and CMS [9, 10, 11, 12, 13].

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Top quark measurements at the LHC

$t\bar{t}$ production cross section. The $t\bar{t}$ production cross section is known from theory to next-to-leading order (NLO) in α_s, including next-to-leading logarithmic (NLL) contributions from soft gluon re-summation, and amounts to 833 ± 100 pb [14, 5] for $m_t = 175$ GeV. Although a complete next-to-next leading order (NNLO) is still unavailable [15], the complete re-summation of next-to-next-to-leading logarithms (NNLL) has been performed [16]. Assuming a top quark mass of $m_t = 175$ GeV and using the CTEQ6.6 PDF parametrization, the expected $t\bar{t}$ cross section at $\sqrt{s} = 14$ TeV (10 TeV) is 827^{+27}_{-62} pb (374^{+18}_{-33} pb) following the prescription used in [16]. By using a simple counting experiment method, CMS will measure the $t\bar{t}$ production cross section by looking into the dileptonic final state topology $t\bar{t} \to bW^+\bar{b}W \to b\bar{b}\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$ ($\ell = e, \mu$), already at an early stage of data taking with only 10 pb^{-1} (see [10] for details). In Fig. 1(a) the number of expected events is shown for all di-lepton channels combined (for 10 pb^{-1}) in bins of jet multiplicity. While the first two bins are used to evaluate the background, by selecting events with $N_{\text{jets}} \geq 2$, a statistical uncertainty of 9% is achieved on the cross section measurement with a signal to background ratio (S/B) of 7 to 1. If backgrounds prove difficult to control, the analysis could be limited to only the $e\mu$ channel with larger uncertainty (13%) but improved S/B (25 to 1). With increasing statistics, more robust event counting methods may be applied [11]. For 100 pb^{-1}, a total of 160 dileptonic signal events are expected against a residual background of 3 events. In Fig. 1(b), a very clean signal can be seen in the CMS $E_{\text{T}}^{\text{miss}}$ distribution for the $e\mu$ channel [11]. For the $t\bar{t}$ semileptonic channel studies, ATLAS used a commissioning analysis optimised for early data that does not rely on b-tagging. Events were selected by requiring one isolated lepton (e or μ) with $p_{\text{T}} > 20$ GeV, $E_{\text{T}}^{\text{miss}} > 20$ GeV and at least four (and three) jets with $p_{\text{T}} > 30$ GeV (and $p_{\text{T}} > 40$ GeV) [8]. In Fig. 1(c) the top quark invariant mass distribution of all events that passed the semileptonic selection (normalized to 100 pb^{-1}) is shown. The precision for the $t\bar{t}$ cross section measurement in the semileptonic channel, taking also into account systematic uncertainties, is expected to be better than 20% [8] for 100 pb^{-1}.

Single top quark production cross section. Single top quark production at the LHC occurs through three different processes: the t-channel, the associated production (Wt) and the s-channel. At NLO the cross section for the t-channel, the dominant process at LHC, is $155.9^{+7.5}_{-7.7}$ pb (for single t production) and $90.7^{+4.3}_{-4.5}$ pb (for single $\bar{t}$ production) [17]. For the associated production and s-channel processes, NNLO calculations are available [18]: for the s-channel, the value for single t ($\bar{t}$) production is $7.23^{+0.55}_{-0.47}$ pb ($4.03^{+0.14}_{-0.16}$ pb); for the associated production, both single t and $\bar{t}$ have equal cross sections which, at NNLO, are 41 ± 4 pb. All cross sections assume $m_t = 175$ GeV and $\sqrt{s} = 14$ TeV at the LHC.

The t-channel process is most likely the best candidate to first observe single top production at the LHC. As there are common features between all single top processes, a common pre-selection was applied in ATLAS [8]. As in the analysis no variable was found to reject effectively the dominant $t\bar{t}$ background, multivariate techniques, like Boosted Decision Trees (BDT), were applied. These techniques improved the S/B ratio of the final selection to 1.31 [8] and establish an expected uncertainty on the t-channel cross section measurement of $\pm 23\%$ (including systematic uncertainties), for 1 fb^{-1}. The estimated precision on the measured value of V_{tb} is 12%. In Fig. 2(a) the top quark invariant mass distribution for the t-channel is shown, after the BDT cut. With increasing luminosity, the Wt and s-channels become within reach of the LHC. For 10 fb^{-1}, CMS estimates uncertainties of 10%, 27% and 36% for the t-channel, associated production (semileptonic channel) and s-channel respectively [9].

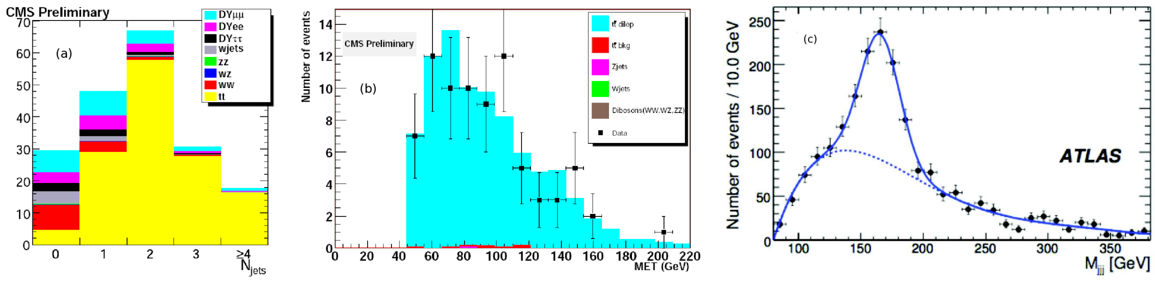

FIGURE 1. Expected number of events for CMS (a) for 10 pb^{-1} in bins of jet multiplicity including all dileptonic *ee*, $e\mu$ and $\mu\mu$ channels, (b) for 100 pb^{-1} in bins of missing transverse momentum for the dileptonic channel $e\mu$ only, and (c) for ATLAS and 100 pb^{-1} for the reconstructed top quark mass from the commissioning analysis.

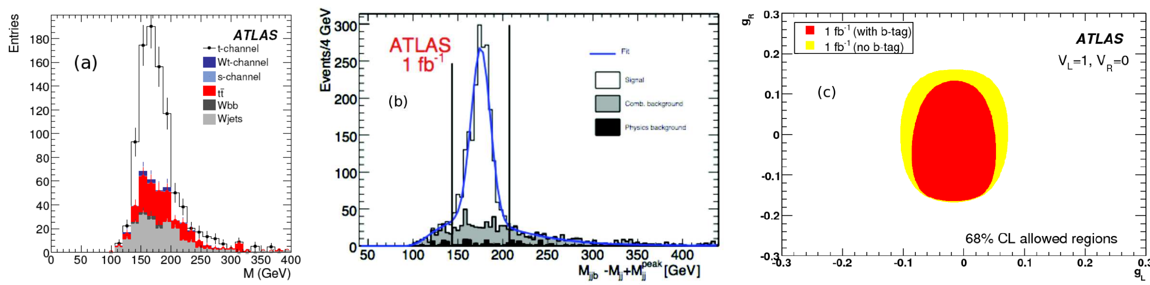

FIGURE 2. (a) leptonic top quark mass distribution after a BDT cut for the single top quark *t*-channel analysis, (b) hadronic top quark mass reconstructed with the geometric method for semileptonic $t\bar{t}$ events and (c) expected 68% C.L. allowed regions for the Wtb anomalous couplings (with and without using the *b*-jets tagging in the analysis)

Top quark mass. The top quark mass is an important parameter of the Standard Model. A precise determination of its value allows stringent limits to be set on the Higgs boson mass (when combined with precise measurements of the W boson mass) and gives sensitivity to physics beyond the Standard Model via their contributions to precision observables. Several methods to evaluate the top quark mass were studied at the LHC. ATLAS used $t\bar{t}$ semileptonic events to evaluate the precision for the mass measurement with an integrated luminosity of 1 fb^{-1} [8]. The mass of the W boson candidate which decayed hadronically ($m_{\rm jj}$) is reconstructed using the two closest light jets (geometric method). The *b*-jet closest to this W boson is used to reconstruct the top quark. Its mass is shown in Fig. 2(b) (for details see [8]). The statistical uncertainty of the top quark mass will be overwhelmed by the systematic error with a few fb^{-1}, and is dominated by the uncertainties on the jets energy scales. In particular the *b*-quark (light quark) jets contribute 0.7 (0.2) GeV to the mass measurement uncertainty per percent of energy scale miscalibration [8]. If jet energies are calibrated within 1 to 5%, a precision of the order of 1 to 3.5 GeV should be achievable with 1 fb^{-1}.

Top quark properties. The ATLAS analysis of the top quark charge [8] shows that, using the weighting technique, is possible to establish with 0.1 fb^{-1}, if the top quark has the Standard Model charge or if it is an exotic particle with charge $-4/3$, with 5σ significance. The top quark spin correlations were studied by both ATLAS and CMS using semileptonic $t\bar{t}$ events. Reconstructed angular distributions were used to set the precision of the spin correlation parameters A

and A_D [8] to 50% and 34%, respectively (ATLAS with 1 fb^{-1}). With increasing statistics the precision of such measurements is improved and, with 10 fb^{-1} CMS obtains a precision of 20% on the measurement of the A parameter. Care must be taken when comparing the ATLAS [8] and CMS [9] expectations with the Standard Model predictions once in the ATLAS analysis a cut is applied on the $t\bar{t}$ mass distribution (to below 550 GeV) to enhance the spin correlations. The absolute uncertainty expected by ATLAS, with 1 fb^{-1}, for the measurements of the W boson longitudinal (F_0), left-handed (F_L) and right-handed (F_R) helicities is 0.045, 0.036 and 0.028 respectively. ATLAS has used the W boson polarization ratios ($\rho_R = F_R/F_0$ and $\rho_L = F_L/F_0$) together with the angular asymmetries (A_+ and A_-) [19] to set limits on the anomalous couplings (g_R, g_L and V_R). In Fig. 2(c) the ATLAS two-dimensional 68% C.L. allowed regions for g_R versus g_L is shown, for 1 fb^{-1}.

Top quark rare decays through FCNC processes ($t \to qZ, q\gamma, qg$) are highly suppressed in the Standard Model [20]. These processes were studied at ATLAS and CMS using $t\bar{t}$ events. Expected limits on the branching ratios were set by ATLAS [8] at 95% CL (in the absence of signal) to 6.8×10^{-4}, 2.8×10^{-3} and 1.2×10^{-2} for the $t \to q\gamma$, $t \to qZ$ and $t \to qg$ channels respectively. CMS has studied these branching ratios for the case in which new physics appear with a 5σ significance [9]. The values obtained for the $t \to q\gamma$ and $t \to qZ$ branching ratios are 8.4×10^{-4} and 14.9×10^{-4}, respectively (10 fb^{-1}). The discovery potential of the ATLAS experiment for the $t\bar{t}$ resonances decaying in the semileptonic channel, was studied as a function of the resonance mass. ATLAS may be able to discover a $t\bar{t}$ resonance with $m_{t\bar{t}} = 700$ GeV, with 1 fb^{-1}, if the product of the production cross section and the branching ratio to a $t\bar{t}$ semileptonic final state is higher than 11 pb [8].

Conclusions

The prospects for top quark physics at the LHC, assuming a center-of-mass energy of 14 TeV and integrated luminosities in the range between 10 pb^{-1} and 10 fb^{-1}, were reviewed using the most up to date projections from the ATLAS and CMS experiments. With the start up of the LHC, a precision era will begin for top quark physics.

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