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Early prospects for top quark physics at the LHC

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Early prospects for the top quark physics program of the ATLAS and CMS experiments at LHC are presented. The methods foreseen and the achievable precision during the first year of operation are emphasized. In particular, expectations for the cross section measurements of $t\bar{t}$ pairs and single top, and for the sensitivity to high mass $t\bar{t}$ resonances are reviewed.

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1. Introduction

Due to its high mass (173.1 ± 1.3 GeV/c^2 [1]), the top is the only quark to decay before hadronisation (with BR(t $\rightarrow$ Wb) $\simeq 1$). The top quark is thus an ideal probe of the standard model through its mass, spin and decay properties. The top quark is also by far the heaviest fermion. Its coupling to the Higgs boson is large, which may be a hint for the top quark contribution to new physics processes.

The main production mode is by strong interaction with an expected total cross section of about 400 (900) pb in pp collisions at LHC center of mass energy $\sqrt{s} = 10$ (14) TeV: with about 90% gg $\rightarrow$ t$\bar{\text{t}}$ at LHC whereas q$\bar{\text{q}}$ $\rightarrow$ t$\bar{\text{t}}$ is about 85% at Tevatron. The electroweak production of single top has an expected cross section of about 130 (250) pb in the t-channel at $\sqrt{s} = 10$ (14) TeV.

Due to these high cross sections, the top quark plays a central role in the LHC physics program: about one top pair will be produced per second at a luminosity of 10^{33}cm^{-2}s^{-1} at $\sqrt{s} = 14$ TeV, providing many events with high transverse momentum, p_T, leptons (e, μ, τ), jets (including b-jets) and large missing transverse energy, $\not{E}_T$. Final states of t$\bar{\text{t}}$ events are dileptons (ee/eμ/$\mu\mu$+jets: 6% of the cases), semileptonic (e or μ+jets: 34%), all hadronic (46%) and (hadronic) $\tau(\tau)$+jets. The dileptons have the cleanest topology (llbb+$\not{E}_T$), semileptonic events (lbbjj+$\not{E}_T$) are rather clean and abundant whereas the all hadronic (bbjjjj) and tau events have a much larger background.

The main background sources are QCD multi-jet events, W+jets and Z+jets, but single top can also contribute to the t$\bar{\text{t}}$ selection, whereas di-bosons events have a small cross section. Typically at $\sqrt{s} = 10$ TeV, leptonic final states of Z (W) decays have a cross section of one (two) order(s) of magnitude larger than the overall t$\bar{\text{t}}$ production, respectively. Requiring a jet of $p_T > 80$ GeV/c, the QCD multi-jet cross section is about three to four orders of magnitude larger than the t$\bar{\text{t}}$ one. The LHC will run at a reduced center of mass energy in the first half of 2010: the signal cross sections are roughly reduced by a factor two between $\sqrt{s} = 10$ TeV and 7 TeV, whereas the W+jets and Z+jets backgrounds are reduced by a factor of about $1.6 - 1.7$.

Top quark events will be both the signal for detailed tests of the standard model, but also, due to their peculiar topology, one of the main backgrounds for new physics searches. It is thus essential to properly handle the reconstructed objects from top decays. In semileptonic t$\bar{\text{t}}$ events, the known W boson mass will help to improve the jet energy resolution for light quark jets from t $\rightarrow$ Wb (with W $\rightarrow$ jj) decays. The presence of two b-jets in t$\bar{\text{t}}$ events will allow a direct measurement of the b-tagging identification efficiency, and an improvement of the b-jet energy resolution.

Both ATLAS [2] and CMS [3] are multi-purpose experiments, devoted to precisely reconstruct and identify the charged leptons, photons, jets and $\not{E}_T$ necessary to perform top quark physics measurements, as well as Higgs boson and new physics searches. Continuing the successful restart of the machine and first collisions at $\sqrt{s} = 900$ GeV and 2.36 TeV by the end of 2009, the collision energy will be increased to $\sqrt{s} = 7$ TeV in the first part of 2010 before a further increase up to 10 TeV at best. With a few accumulated 10 pb^{-1} luminosity, top pair events should be rediscovered at LHC and a first cross section measured. With about 100 to 300 pb^{-1}, a more precise top pair cross section should be performed, with a first observation of single top in proton-proton collisions and first searches for new physics with top quark. Most of the results presented here are based on an expected collision energy of 10 TeV, although it will be 7 TeV at the beginning, and an integrated luminosity of less than 200 pb^{-1}, corresponding to the first part of the 2010 LHC schedule.

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2. Top quark event selection

Triggers for top quark events are based on high p_T lepton selection. A first level trigger selects electron candidates using clusters in the electromagnetic and hadronic calorimeters, and muon candidate segments in the muon system. At a higher level, lepton candidates are matched to charged particle tracks with $p_T > 9 - 15$ GeV/c. Electron identification is based on transverse shower profile and hadronic/electromagnetic energy fractions in the calorimeters. Muon identification is mainly based on matching quality between muon segments and inner tracking. A lepton is considered as isolated if a small calorimetric energy or track p_T sum is observed within a cone centered on the lepton direction. The cone radius is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, typically $< 0.2 - 0.3$, where η is the pseudo-rapidity and ϕ the azimuthal angle. Lepton reconstruction and identification efficiencies will be based on "tag-and-probe" techniques with $Z \to e^+e^-/\mu^+\mu^-$ events where one lepton is tightly identified and the other loosely selected.

Semileptonic $t\bar{t}$ events are selected by requiring [4, 5] only one isolated electron or muon of $p_T > 20$ GeV/c in the rapidity range $|\eta| < 2.4 - 2.5$ and at least four energetic jets ($p_T > 30 - 40$ GeV/c). No b-tagging is considered for these first LHC data. No $\not\!\!E_T$ cut is used in CMS whereas ATLAS considers a loose $\not\!\!E_T > 20$ GeV selection or tighter kinematic cuts on the leptons and jets.

Dilepton $t\bar{t}$ events are selected by requiring [6, 7] two, opposite charge, isolated electrons or muons of $p_T > 20$ GeV/c and at least two jets of $p_T > 20 - 30$ GeV/c. In order to reject Drell-Yan events, the dilepton mass is required to lie outside the Z mass window. Due to the presence of two neutrinos, a $\not\!\!E_T > 20$ $(30 - 35)$ GeV selection is applied in the eμ (ee/$\mu\mu$) channel, which removes most of the remaining QCD multi-jet background.

3. Early top quark production cross section

Different scenarios have been considered here for the $t\bar{t}$ cross section prospects: 10 pb^{-1} (20 pb^{-1}) for the dileptonic (semileptonic) channel in CMS, 200 pb^{-1} for both channels in ATLAS. The cross sections are measured by a simple counting of the number of observed selected events, N_{obs}, and expected backgrounds, N_{bgd}, corrected for the signal acceptance, A, reconstruction efficiency, ε, and luminosity, $\mathscr{L}$: $\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{A\,\varepsilon\,\mathscr{L}}$. To be less sensitive to the Monte-Carlo simulation reliability, data driven methods, often inspired from the Tevatron, have been used in both experiments in order to estimate the main background sources.

3.1 Semileptonic $t\bar{t}$ channel

The amount of reconstructed and isolated leptons is difficult to predict in QCD multi-jet events. Two methods have been considered in CMS to estimate this contribution [4]. The first one relies, for μ+jets events, on the muon impact parameter significance and on the muon isolation variable. The "ABCD method" uses these two weakly correlated variables in background dominated regions (BCD), whose contribution can be extrapolated in the signal (A) region (Fig. 1, left): $N_A = N_B N_C / N_D$. The second method extrapolates the lepton (e or μ) isolation variable from the QCD dominated region to the signal one. The shape of the QCD distribution is estimated from a low $\not\!\!E_T$ sample. A consistency check is performed as a function of the jet multiplicity.

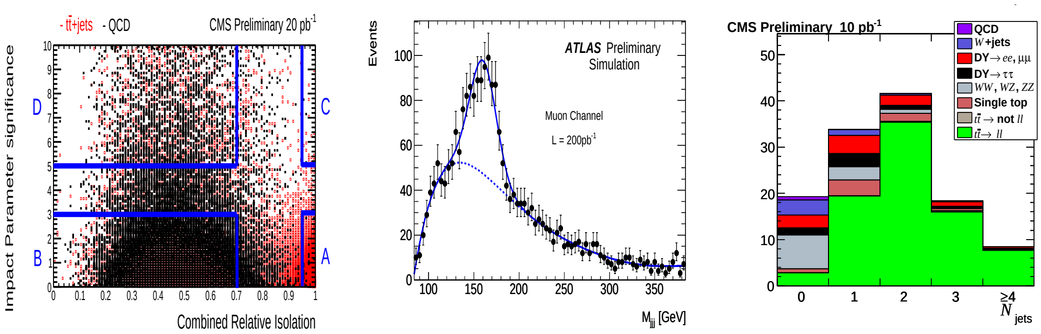

Figure 1: Example of plot illustrating the ABCD method [4] (left). Fit to the reconstructed hadronic top quark mass in ATLAS μ+jets channel with 200 pb^{-1} [5] (middle). Number of jets in CMS $e\mu$+jets channel with 10 pb^{-1} [6] (right).

The estimate of the W+jets background from data can be obtained in the following way. A Z sample is used in ATLAS in order to measure the Z/W ratio for different jet multiplicities [5]. A control region (CR) is defined for 1 or 2 jets, whereas the signal region (SR) requires ≥ 4 jets. The simulation is only used to estimate the double ratio $C_{\mathrm{MC}} = \frac{W^{\mathrm{SR}}/W^{\mathrm{CR}}}{Z^{\mathrm{SR}}/Z^{\mathrm{CR}}}$ with reduced systematic uncertainties, in order to get: $(W^{\mathrm{SR}}/W^{\mathrm{CR}})_{\mathrm{data}} = (Z^{\mathrm{SR}}/Z^{\mathrm{CR}})_{\mathrm{data}} \cdot C_{\mathrm{MC}}$, with an overall $\pm 20\%$ uncertainty on the W+jets normalisation. With the same integrated luminosity of 200 pb^{-1}, the W boson charge asymmetry in pp collisions has also been used in CMS to estimate the W+jets yield in the μ+jets channel [4].

Finally the amount of $\mathrm{t\bar{t}}$ events can be estimated from a fit to the reconstructed hadronic top quark mass (Fig. 1, middle). In order to reduce the large combinatorial background, the most favoured lb+bjj combination is selected with the highest scalar sum of p_T or by minimising, in CMS, the χ^2 of the W boson and top quark invariant masses. The shape of the residual combinatorial background can be estimated by reverting a cut in the W mass window or by using QCD events in ATLAS, or by choosing events with a high χ^2 in CMS. The systematic uncertainty, not including the luminosity, on the measured cross section is typically estimated to be $\pm 20\%$ ($\pm 10\%$) at 20 pb^{-1} (200 pb^{-1}), with a similar (or even smaller, depending on the method) statistical error.

Measuring the top quark mass with ± 1 GeV accuracy will require a $\pm 1\%$ precision on the jet energy scale. Inversely, the semileptonic top pair events can be used to improve the jet energy resolution. Several studies were performed at $\sqrt{s} = 14$ TeV: in ATLAS [8] (CMS [9]) e+μ (μ) events, imposing the W (W and top) mass constraint, a precision of $\pm 2\%$ ($\pm 1\%$) on jet energy can be reached for light (light+b) quarks with 50 pb^{-1} (100 pb^{-1}). Of course much more statistics will be needed for detailed p_T/η studies.

3.2 Dileptonic $\mathrm{t\bar{t}}$ channel

Different approaches are chosen in CMS (10 pb^{-1} [6]) and ATLAS (200 pb^{-1} [7]) to estimate the main backgrounds from the data. The Drell-Yan ee and $\mu\mu$ events are estimated in CMS by simple counting in the Z mass window, using the simulation to extrapolate outside. In ATLAS, the ABCD method is used in the $\not{E}_T/$ Z mass plane, with reduced uncertainties. The fake leptons are estimated in CMS by relaxing the lepton identification and isolation in a QCD multi-jet sample. In ATLAS, fake efficiencies are measured by comparing low and high $\not{E}_T$ regions. The number of real and fake leptons is obtained by solving a system of equations for loose and tight lepton pair combinations.

A rather pure signal is obtained especially in the eμ channel (Fig. 1, right). The systematic uncertainty, not including the luminosity, on the combined dilepton cross section is estimated to be about $\pm 10\%$ with statistical error of $\pm 15\%$ with 10 pb^{-1}.

The b-tagging can be used to further reduce the background and to get the number of events with 0, 1 or 2 b-tagged jets. This allows to infer the ratio $R = BR(\mathrm{t} \to \mathrm{Wb})/(\Sigma_{\mathrm{q=d,s,b}}\mathrm{t} \to \mathrm{Wq})$ which is quite close to 1 for a standard model with three families of fermions. With 250 pb^{-1} in the eμ channel, CMS expects a $\pm 10\%$ precision on R, dominated by the uncertainty on the b-tag efficiency [10].

3.3 Single top

Although the single top production cross section is rather high at LHC, the backgrounds (including $\mathrm{t\bar{t}}$ pairs) are large and more severe selection cuts have to be applied [8, 11]. Similarly to the $\mathrm{t\bar{t}}$ analysis, μ+jets events are selected in CMS [11]. However, events are required to contain only two jets, including only one b-tagged jet, in order to enhance the single top t-channel contribution ($\mathrm{q'b} \to \mathrm{W}^* \to \mathrm{\bar{q}t} \to \mathrm{\bar{q}b}\mu^+\nu_\mu$) which allows a direct measurement of the CKM matrix element $|V_{\mathrm{tb}}|$. A fit to the transverse W boson mass is used to estimate the QCD and W+jets background and a selection $m_T(\mathrm{W}) > 50$ GeV/c^2 reduces them further. Then a fit to the polarisation angle $\theta^*(\mathrm{\bar{q}}\mu)$ in the top quark rest frame is performed: neglecting the luminosity systematic, the sensitivity to the single top t-channel is about 2.7 (5) standard deviations with 200 (700) pb^{-1} at $\sqrt{s} = 10$ TeV.

4. Search for high mass $\mathrm{t\bar{t}}$ resonances

Several theories beyond the standard model predict enhanced couplings to the third family top quark. Prospects for a search for a narrow Z' resonance ($\Gamma_{Z'}/m_{Z'} \simeq 1\%$), decaying to $\mathrm{t\bar{t}}$, is presented here. Tevatron experiments already set a limit on a leptophobic Z' with mass $m_{Z'} > 805 - 820$ GeV/c (95% CL) [12].

For $m_{Z'}$ up to 2 TeV/c^2, CMS is considering a "classical" isolated μ + ≥ 4 jets study where all final jets are separately reconstructed [13]. The QCD and W+jets backgrounds are estimated from the muon-to-closest jet angle and p_T distributions. With 100 pb^{-1} at $\sqrt{s} = 10$ TeV, the 95% C.L. expected cross section limit on Z' $\to \mathrm{t\bar{t}}$ is 8.3 pb for $m_{Z'} = 2$ TeV/c^2.

For $m_{\mathrm{t\bar{t}}} > 2$ TeV/c^2, the challenge is to reconstruct highly boosted top quark decay products as a monojet, while keeping the backgrounds under control. A dedicated algorithm has been developed in CMS [14]. In the fully hadronic $\mathrm{t\bar{t}}$ final state, subjets are used to reconstruct the W boson and top quark masses whose known values help to reject QCD and W+jets events and to estimate their remaining contribution. As previously, the 95% C.L. limit is 1.5 (0.7) pb for $m_{Z'} = 2$ (3) TeV/c^2. A search with boosted μ+jets events in CMS has also been performed.

ATLAS is also using a dedicated algorithm in the semileptonic e or μ+jets events [15]. A likelihood is built, based on kinematic quantities, in order to separate the Z' signal from the QCD and W+jets background. The obtained Z' mass resolution is $\sigma_m/m = 5\%$. With 1 fb^{-1} at $\sqrt{s} = 14$ TeV, the 95% C.L. limit is 0.6 (0.2) pb for $m_{Z'} = 2$ (3) TeV/c^2.

5. Conclusion

The top quark physics program at LHC is rich and opens a new window for detailed tests of the standard model and for the search for new physics. Observing top quark events in the early running of LHC is challenging because it requests the simultaneous reconstruction and identification of most physics objects: jets, muons, electrons, as well as taus, missing transverse energy and b-tagging. Both ATLAS and CMS have prepared and developed methods to estimate the reconstruction and identification efficiencies, and to infer the main backgrounds, from the real data. These methods will of course improve with higher integrated luminosities and will help to study the top quark properties in detail. After a first stage of basic measurements (top quark rediscovery, first cross section measurements in various final states), increase in luminosity and in collision energy will allow the search of new physics in the top quark sector. As a new energy domain will be explored at the LHC, an early surprise may happen.

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