Top Physics at ATLAS and CMS

Francesco Spanò
(on behalf of the ATLAS and CMS collaborations)
Columbia University, Nevis Laboratories, 136 South Broadway, P. O. Box 137, Irvington, NY 10533, USA

The potential for top quark physics of the ATLAS and CMS experiments at the Large Hadron Collider is surveyed ranging from top quark “re-discovery” and its use as a calibration tool to initial and later stage measurements.

1 Introduction: top quark at the LHC

ATLAS\(^1\) and CMS\(^2\) are complementary multi-purpose detectors aimed at measuring the properties of leptons, hadrons and photons in proton-proton (pp) collisions at the Large Hadron Collider\(^3\) (LHC). On its way to reach the design center-of-mass energy (\(\sqrt{s} = 14\) TeV) and instantaneous luminosity (\(L = 10^{34}\) cm\(^{-2}\) s\(^{-1}\)), in 2009-2010 the LHC is expected to run at \(\sqrt{s} = 10\) TeV, delivering an integrated luminosity (\(\int L dt\)) of the order of 0.2 fb\(^{-1}\).\(^3\) All results reported in this paper are derived from simulated collisions at \(\sqrt{s} = 14\) TeV.

At LHC with \(\sqrt{s} = 14\) TeV top quark pair (t\(\bar{t}\)) production cross section\(^4\) (\(\sigma_{t\bar{t}}\)) is about 900 pb with a theoretical uncertainty of order 10\% and a resulting rate of about 0.9 Hz already at \(L = 10^{33}\) cm\(^{-2}\) s\(^{-1}\). The single top quark production\(^5\) is dominated by t-channel diagrams that account for about 76\% of the total cross section (\(\sigma_t\)) of about 320 pb. For LHC with \(\sqrt{s} = 10\) TeV, \(\sigma_{t\bar{t}}\) drops\(^4\) to \(\approx 400\) pb and, while \(\sigma_t\) remains about three times smaller than \(\sigma_{t\bar{t}}\), the relevant \(W + n\) jets background cross section (with \(n > 1\)) decreases by \(\approx 23\%\): this results into a somewhat worse signal to background ratio (S/B) for t\(\bar{t}\) in comparison to \(\sqrt{s} = 14\) TeV.

As the top quark decays to a \(W\) boson and a \(b\)-quark with a branching fraction (BR) of almost 100\%, the t\(\bar{t}\) final state features a \(b\)-jet pair associated with high transverse momentum (\(p_T\)) light jets when each \(W\) boson decays to quarks (fully hadronic channel with BR \(\approx 44.4\%\)) and one (\(\ell +\)jets channel with BR \(\approx 44.4\%\)) or two high \(p_T\) lepton(s) (\(\ell\ell\) channel with BR \(\approx 11.2\%\)) and sizeable transverse missing energy (\(E_{T}^{\text{miss}}\)) in the cases where one or two \(W\) bosons decay to leptons respectively. The final states of single top quark and t\(\bar{t}\) can be obtained from
one another by swapping one \( t \rightarrow Wb \) leg of the \( t\bar{t} \) decay with a \( W \) boson (\( Wt \) channel) or one/two quarks (\( s \) and \( t \)-channels), one of which is a \( b \)-quark. The two final states then have similar backgrounds (single bosons (\( W, Z \)) plus jets, di-bosons and Quantum Chromodynamics (QCD) multi-jet events) and they are background to each other.

2 Re-discovering Top

A clean and robust analysis is required to re-establish the top quark signal with early data.

An example CMS analysis\(^8\) uses a realistic first day simulation of the detector mis-calibration and misalignment. The distinguishing features of the \( \ell+\)jets final state (one central high \( p_T \) muon (\( \mu \)) and four or more central high \( p_T \) jets) are coupled to additional \( \mu \) isolation cuts (on energy deposited in a calorimeter cone around the \( \mu \) and the \( \mu \) spatial distance from the closest jet) to achieve a drastic reduction of the large QCD background. With only \( \int L dt = 10 \text{ pb}^{-1} \) the \( t\bar{t} \) signal is expected to emerge from the background in the high jet multiplicity bins (\( N_{\text{jets}} \geq 4 \)) with about 130 signal events and \( S/B \approx 1.4 \) as shown in figure 1 (left). No \( b \)-tagging or \( E_T^{\text{miss}} \) cuts are used. The size and shape of the QCD background have large uncertainties and its data-driven determination is a crucial ingredient in the analysis.

![Figure 1: Left: CMS reconstructed jet multiplicity distribution for \( t\bar{t} \) events passing the final selection with CMS detector except for the requirement \( N_{\text{jets}} \geq 4 \). Center and Right: simulated \( e\mu \) templates in the plane of \( E_T^{\text{miss}} \) and number of jets for \( t\bar{t} \) and \( W+\)jets samples as seen by the ATLAS detector. See text for references.](image)

Once the signal is established, the lower \( BR \) \( \ell\ell \) final state provides a clean sample to measure \( \sigma_{t\bar{t}} \).\(^9\)\(^10\) The selections of both ATLAS and CMS require two high \( p_T \) isolated leptons with opposite charges and large \( E_T^{\text{miss}} \) that is not collinear with any of the two leptons or with the leptonic system. In an example from ATLAS \( \sigma_{t\bar{t}} \) is derived even without any additional cuts (no \( b \)-tagging) by a likelihood fit of the signal to simulated templates of distributions in the \( E_T^{\text{miss}} \)-jet multiplicity space.\(^a\) As one can see in figure 1 (center and right), \( t\bar{t} \) events show higher multiplicity and somewhat higher \( E_T^{\text{miss}} \) than \( W+\)jets background. With \( \int L dt = 100 \text{ pb}^{-1} \) such an analysis\(^9\)\(^10\) has an outstanding significance (\( \approx 20 \)) which is already \( \approx 7 \) with \( \int L dt = 10 \text{ pb}^{-1} \): the \( \ell\ell \) channel can also be used to establish the \( t\bar{t} \) signal. For \( \int L dt = 100 \text{ pb}^{-1} \) the ATLAS fractional uncertainty on \( \sigma_{t\bar{t}} (\delta \sigma_{t\bar{t}}/\sigma_{t\bar{t}}) \) shows comparable systematic and statistical contributions (7% and 4% respectively).\(^b\) The crucial analysis requirements are to validate the \( E_T^{\text{miss}} \) description and perform data-driven background estimates.

The more statistically powerful \( \ell+\)jets channel (\( \ell = e, \mu \)) is also used to extract \( \sigma_{t\bar{t}} \) by requiring one high \( p_T \) central lepton and four or more central high \( p_T \) jets. The reconstruction

\(^a\)Other methods use additional cuts on the number of jets and their transverse momentum to purify the sample. With no \( b \)-tagging the cross section is extracted by counting the events in multiplicity bins or performing a likelihood fit to angular variables (ATLAS)\(^9\)\(^10\) while the use of \( b \)-tagging and \( W \) mass constraint can also be added (CMS)\(^9\).

\(^b\)CMS estimates that for \( \int L dt = 1 \text{ fb}^{-1} \) the statistical contribution is expected to drop to 0.9% compared to a dominant systematic contribution of \( \approx 11\% \) (see section 8.1.2 of\(^7\)).
of the hadronic top is used to enhance the signal over the dominant $W+$jets background when no $b$-tagging is used. Figure 2 (left) shows the ATLAS result\(^7\) for $\int L dt = 100 \text{ pb}^{-1}$ where the hadronic top consists of the three jets with the highest total $p_T$ and at least one di-jet pair is required to have a mass consistent with the $W$ boson.\(^8\) Then $\sigma_T$ can be extracted by a likelihood fit to the mass shape (ATLAS) or by simply counting events after subtracting the expected background (ATLAS, CMS). For $\int L dt = 100 \text{ pb}^{-1}$ the ATLAS $\delta\sigma_T/\sigma_T$ in a robust counting experiment\(^9\) is already systematic-dominated ($\approx 17\%$ compared to $3\%$ statistical contribution). The main initial systematic uncertainties are the jet energy scale (JES) and the normalization of the $W+$jets background which, like the estimate of the uncertain QCD background, benefits from a data driven approach. A precise ($5\%$) measurement of the $b$-tagging efficiency will be necessary for it to be used effectively in the cross-section measurement.

3 Top for Calibration

The established $\ell+$jets sample can be used (together with the di-lepton (CMS)) to measure the $b$-tagging efficiency $\epsilon_b$. By exploiting cuts on the kinematic and topological properties or by cutting on likelihood discriminants, it is possible to select a highly enriched $b$-jet sample in which, after background subtraction, $\epsilon_b$ can be measured\(^11\), also as a function of the $b$-jet pseudo-rapidity and transverse energy ($E_T$)(also see section 12.2.8.1 of\(^2\)). CMS shows an example of this determination in figure 2 where $\epsilon_b$ is shown to vary from 30\% to 60\% in the $E_T$ range (50 GeV, 250 GeV) for the barrel section using $\int L dt = 1 \text{ fb}^{-1}$. With $\int L dt = 1 \text{ fb}^{-1}$ an uncertainty on $\epsilon_b$ of 6\% in the barrel and of 10\% in the endcaps is expected\(^2\). ATLAS showed that a global average $\epsilon_b$ can be known at the 5\% level with $\int L dt = 100 \text{ pb}^{-1}$by performing a likelihood fit to the expected number of events with zero to three $b$-tagged jets\(^11\) ($\epsilon_b$, the $c$-tagging efficiency and $\sigma_T$ are determined simultaneously).

Once $b$-tagging is understood the $\ell+$jets sample can be used to identify the $b$ and the $W$ di-jet system that result from the “hadronic” top decay (for high $p_T$ jets). In this way in ATLAS the global average JES for light jets is expected to be known at the 2\% level even with 50 pb$^{-1}$ by performing a $\chi^2$ fit to di-jet mass simulated templates when varying the overall light jet scale ($\alpha$) and resolution ($\beta$) with respect to the default.\(^11\) An example of such technique is shown in figure 2 (right). Differential information on the light JES can be known at about 2\% with $\int L dt = 1 \text{ fb}^{-1}$ by using re-scaling techniques\(^11\), while CMS expects that exploiting the top quark

$^4$The addition of one or two $b$-tagged jets improves S/B\(^6\) (ATLAS) and with two $b$-tagged jets and cleanly separated jets, a convergent kinematic fit imposing the $W$ mass constraint to the light di-jet system can be used to select events (see section 8.1.3 of\(^7\)) (CMS).

$^4$A 10\% uncertainty is expected by ATLAS for $\int L dt = 100 \text{ pb}^{-1}$.
mass measured at the Tevatron can provide knowledge of the average $b$ JES\cite{13} at the % level with $\int L dt = 100 \text{ pb}^{-1}$.

4 Measuring Top

4.1 Top Quark Mass

Equipped with better understanding of $b$-tagging and JES, the top quark mass ($m_{\text{top}}$) can be measured in the $\ell+\text{jets}$ channel by using the same selection required for $\sigma t\bar{t}$ measurements and requesting at most harder jets (ATLAS) to suppress backgrounds. The hadronic $W$ is reconstructed even with minimal or no $b$-tagging information and it is then associated with the closest jet or $b$-jet by its spatial (ATLAS) or kinematic (ATLAS/CMS) distance\cite{14,15}. The top quark mass value is then derived by either fitting an analytic function (ATLAS), extrapolating or performing a more sophisticated event-by-event likelihood fit (CMS). An example from ATLAS is shown in figure 3 after $b$-tagging, a nearly background-free scenario is obtained where the reconstructed top mass is fitted by a Gaussian plus a “threshold function”\cite{14}. The measurement is quickly systematics dominated, mainly by the jet energy scale (particularly the $b$-jet scale).

A top quark mass uncertainty of the order of 1 to 5 GeV is expected to be achievable\cite{14,15} with $\int L dt = 1 \text{ fb}^{-1}$ if the uncertainty on the JES is in the range of 1% to 5% respectively. The fully hadronic and $\ell\ell$ channel also have mass information, but the extraction is harder due to the increased level of combinatoric background and the final state neutrinos.

Alternative techniques to measure the top quark mass are also considered to reduce the impact of JES systematic uncertainty. In an example from CMS\cite{16}, $\ell+\text{jets}$ events are sifted through to find exclusive $b$-jet decays to $J/\Psi$ (with the $b$-jet coming from $t \rightarrow Wb \rightarrow \ell\nu b$ chain). The top quark mass is strongly correlated with the mass of the system formed by the $J/\Psi$ and the lepton from the “leptonic” top decay as it is shown in the calibration curve by CMS in figure 3. The systematic uncertainty is dominated by theoretical contributions (mainly from models of $b$-quark fragmentation and underlying event) while the JES contribution is negligible. Given the low BR rate for $t\bar{t}$ event to produce a final state with a leptonic $J/\Psi$\cite{16}, a top quark mass uncertainty of about 2 GeV is expected for $\int L dt = 20 \text{ fb}^{-1}$.

4.2 Single top quark

Once the $t\bar{t}$ signal is established and measured, the attention can turn to measuring $\sigma t$ in the dominant $t$-channel where one top quark decays leptonically (the final state is then $q\ell\nu\bar{b}(b)$).

\footnote{For instance CMS expects\cite{16} top quark mass uncertainties of about 1.2 GeV in the $\ell\ell$ channel with $\int L dt = 10 \text{ fb}^{-1}$ and 4.2 GeV in the fully hadronic channel with $\int L dt = 1 \text{ fb}^{-1}$\cite{16}.}
tend to select events consistent with a final state is a $Z$ boson. Additional cuts on the masses and the angular relation of the one light jet and two isolated opposite-sign leptons whose di-lepton mass is consistent with the (one b variables and a set of BDT outputs based on twenty-five variables, the evidence with about 30 fb$^{-1}$.

In an example from ATLAS, a complex set of kinematic cuts (on the final state lepton, the $b$-jet and the distinctive single forward light jet) is coupled to a multivariate Boosted Decision Tree (BDT) based on a set of shape variables to separate the signal from the background. The distribution for the top quark mass after all cuts for $\int L dt = 1 \text{ fb}^{-1}$ is shown in figure 4 (left) where the single top signal is standing out of the remaining $t\bar{t}$ and $W+$jets backgrounds. With these techniques S/B is expected to be about 1.3 with $\delta \sigma / \sigma_t$ dominated by systematic contributions even for $\int L dt = 1 \text{ fb}^{-1}$. Given the sizeable background to be overcome, the $t\bar{t}$ signal knowledge from the data is required in addition to the $W+$jets and the QCD signals. In addition an excellent detector understanding is required ($b$-tagging performance, JES) also to control the BDT inputs. The less statistically powerful $Wt$ channel is very similar to the $t\bar{t}$ signal in its final state (one $b$-jet less). So, as ATLAS shows in figure 4 (center), even after cuts on a set of kinematic variables and a set of BDT outputs based on twenty-five variables, the $t\bar{t}$ background is still sizeable. This results into an expected S/B of about 0.4 with $\int L dt = 1 \text{ fb}^{-1}$. Only a few fb$^{-1}$ will allow three standard deviation (s.d.) evidence to be established and a measurement of the cross section with a relative uncertainty of 20% should be in sight with 10 fb$^{-1}$. The lowest BR s-channel is expected to be the most difficult: ATLAS, for instance, expects to achieve a 3 s.d. evidence with about 30 fb$^{-1}$. Even more than for the $t$ channel, both $s$ and $Wt$ channel will require an excellent detector understanding to be coupled to data-driven background estimation techniques and to a good control of the theoretical description of initial and final state radiation (particularly for the $Wt$ channel whose similarity to $t\bar{t}$ makes it more sensitive to jet multiplicity).

5 Top beyond the standard model

Measurements of the properties of the top quark offers a window onto possible physics beyond the standard model. An example from CMS shows the sensitivity to Flavour Changing Neutral Current events where a $t \rightarrow Wb$ leg of the $t\bar{t}$ decay is replaced by a $t \rightarrow Zq$ decay. The resulting final state is $\ell\ell q\ell b$. Cuts are applied to all the expected final state particles: one $b$-tagged jet, one light jet and two isolated opposite-sign leptons whose di-lepton mass is consistent with the $Z$ boson. Additional cuts on the masses and the angular relation of the $Zq$ and $Wb$ systems tend to select events consistent with a $t\bar{t}$ decay. Once the background is subtracted (mainly $\ell\ell t\bar{t}$ events) it is possible to count the events and measure the cross section. Figure 4 (right) shows the cross sections for which a 5 s.d. sensitivity is expected as a function of the collected

$^1$CMS expects to need at least 10 fb$^{-1}$ to measure the cross section with a systematic-dominated uncertainty of about 30%.
integrated luminosity. With $\int L dt = 10 \text{ fb}^{-1}$ a branching ratio of $1.49 \times 10^{-3}$ is expected to be detectable (see section 8.5.4 of [7]). The main systematic uncertainties derive from jet and lepton energy scale and $b$-tagging efficiency.

Acknowledgments

The author would like to thank Martine Bosman, Gustaaf Brooijmans, Tim Christiansen, Richard Hawkings and John Parsons for useful discussions and comments. Additional useful discussions with Jörgen Sjölin and Anne-Isabelle Etienvre are gratefully acknowledged.

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18. See section 8.4.4 of [7].
19. See section 8.5 of [7].