Early physics with top quarks at the LHC

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The ATLAS and CMS experiments are now in their final installation phase and will be soon ready to study the physics of proton-proton collisions at the Large Hadron Collider. The LHC, by producing 2 $t\bar{t}$ events per second, will provide more than 8 million top events a year at start-up. In this paper, particular emphasis is given to the $t\bar{t}$ physics studies that can be performed at the beginning of the LHC running, with a limited amount of integrated luminosity ($\sim$ 10 fb^{-1}).

1 Introduction

In the early days of data taking at the LHC, top physics will have a role of primary importance for several reasons. First of all, since top physics allows for precise studies of the Standard Model (SM) and since the determination of the top mass constraints the Higgs mass via radiative corrections. At start-up, already with the first few fb^{-1} of integrated luminosity and with a non perfectly calibrated detector, a top signal can be clearly separated from the background and the top pair production cross-section can be extracted at better than 20% accuracy and with negligible statistical error. The first measurement of the top mass will provide feedback on the detector performance and top events can be used to understand and calibrate the detector light jet energy scale and the b-tagging. Additionally in scenarios beyond the SM, new particles may decay into top quarks, therefore a detailed study of the top quark properties may provide a hint on new physics. A good understanding of top physics is also essential since top events are a background for many new physics searches.

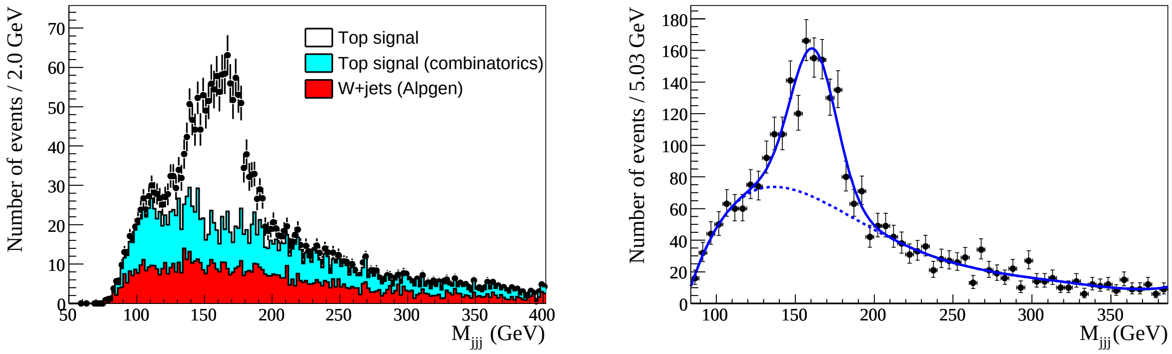

Figure 1: Expected distribution of the three-jet invariant mass after a cut on the di-jet system (left plot) and a t (right plot) in a 100 pb $^{-1}$ event sample.

2 Early selection of top events in the leptons+ jets channel

Since top events are so crucial for the initial phase of data taking, it is important to understand how much integrated luminosity is needed to observe the top signal over the background at startup and the e ects of a non-perfectly calibrated detector on its observability.
A study that uses a very simple selection in the leptons + jets channel, where $t\bar{t} \to W^{+}bW^{-}\bar{b}$ with a W decaying hadronically and the other leptonically $W \to e\nu_e(\mu\nu_\mu)$, has been performed by the ATLAS collaboration [1]. The selection requires 3 jets with transverse momentum $p_T >$ 40 GeV/c and one with $p_T >$ 20 GeV/c, one isolated lepton with $p_T >$ 20GeV/c and missing transverse energy $E_T >$ 20 GeV/c^2. In this selection the b-tagging information is deliberately not used since it might not be optimized and calibrated in the initial phase of data taking. The hadronic top is selected as the 3-jet combination with the highest transverse momentum: 2 out of the 3-jets would be resulting from a W decay, therefore only the combinations with a di-jet invariant mass $|m_{jj} - m_W| <$ 10 GeV/c^2 are kept. Figure 1 shows the expected distribution of the 3-jet invariant mass in a 100 pb^{-1} integrated luminosity sample. The dominant background is the W + jets production giving a contribution of the same order as wrongly reconstructed $t\bar{t}$ events. The signal over background ratio is about 0.7 and the relative statistical error is about 10%. Overall the top cross-section could be determined with a total uncertainty of about 20% with few hundred pb^{-1} of integrated luminosity.

3 Top cross-section evaluation

In the leptons + jets channel, a better accuracy on the cross-section can be obtained by re ning the selection and in particular by requiring 2 b-tagged jets. To further reduce the background and combinatorics, a converging kinematic t to m_W can be applied. With 5 fb^{-1} of integrated luminosity, a recent study by the CMS collaboration [2] has extracted the $t\bar{t}$ cross-section with the following errors: $\Delta\sigma/\sigma = 0.6\%$ (statistical) $\oplus$ 9.2% (systematical) $\oplus$ 5.0% (luminosity).
While the leptons+ jet can be considered as the golden channel since the background can be reduced by using simple cuts and the signal will be visible very soon after start-up, promising results have been obtained also in the di-leptonic and fully hadronic channels, where both W's decay either leptonically (e, μ) or hadronically, respectively. A comparison of the performances in the di erent search channels, as from recent studies by the CMS collaboration [2,3], can be read from Table 3.

Table 1: Breakdown of statistical, systematical and luminosity errors, main background sources, efficiency and signal over background ratio S/B, for the cross-section studies in the lepton+jets, di-leptonic and hadronic channels. The S/B ratio for the lepton+jets channel doesn't take into account the background from $t\bar{t}$.

	syst (%)	stat (%)	lumi (%)	main syst. (%)		main bkg	e	S/B
$10\,\mathrm{fb}^{-1}$ lepton+jets	9.7	0.4	3	b-tag PDF Pile-up	7 3.4 3.2	$t\bar{t}$ W + j	6.3	26.7
$10\,\mathrm{fb}^{-1}$ di-leptonic	11	0.9	3	PDF b-tag Jet E Scale (JES)	5 4 4	$t\bar{t}$ with ($W \to \tau\nu$ and $\tau \to \nu$)l	5	5.5
$1\,\mathrm{fb}^{-1}$ hadronic	20	3	5	JES Pile-Up	11 10	QCD	1.6	1/9

4 The top mass measurement

In the lepton + jets channel, after an event selection optimised not to bias the mass measurement, different methods have been exploited to extract the top mass (m_t). The simplest is to perform a fit to the invariant mass of the 3 jets arising from the hadronic top decay, but this suffers of the impact of poorly reconstructed jets due to effects of FSR and to the semi-leptonic decay of b-quarks. Another method, less affected by systematic errors, reconstructs event by event the entire $t\bar{t}$ final state via a χ^2 minimisation based on kinematic constraints: the energies of the leptons and jets, the jet directions and the 3 components of the reconstructed neutrino's are free to vary within their resolutions; m_t is then fitted in slices of χ^2 and is extrapolated from a linear fit to the m_t value corresponding to $\chi^2 = 0$ [4]. Alternatively, an event-by-event likelihood method which convolutes the resolution function of the event, or the so called ideogram, with the expected theoretical template can be used [5]. A method which is appealing since it has independent systematic errors, is to select high p_T top pairs with $p_T > 200$ GeV/c: in this case the 2 top quarks tend to be back to back and this can be used to reduce the backgrounds. Since the 3 jets on one hemisphere tend to overlap, the energy in a cone around the candidate top quark has to be collected making the measurement less sensitive to the jet energy calibration. A summary of the different contributions to the error on m_t for the different methods described above can be found in table 4, as from an ATLAS study [4].

As for the cross-section, m_t can also be extracted from the di-leptonic and the hadronic channels. The di-lepton channel has a clean signature, but 2 neutrino's need to be reconstructed, this can be done by applying a constrained fit assuming the W mass and two equal masses for the 2 reconstructed top [3]. With an integrated luminosity of 1 fb^{-1}, the statistical error on m_t would be of about 1.5 GeV/c^2 and the systematical about 4.2 GeV/c^2. In the hadronic channel a kinematic fit can be used to reconstruct both top quarks, but the measurement is affected by large QCD backgrounds [3]. With an integrated luminosity of 1 fb^{-1} the statistical error would be of about 0.6 GeV/c^2 and the systematical about 4.2 GeV/c^2.

5 Searches for new physics

By reconstructing the top mass spectrum in $t\bar{t}$ leptons+jets events, resonances originated by the decay process $pp \to X \to t\bar{t}$ can be observed. From preliminary studies by ATLAS a 1(2) TeV=c^2 mass Z^0 boson produced with a cross-section of 4(3) pb can be observed at about 3σ significance with an integrated luminosity of about 5 fb^{-1}.

Table 2: Expected systematical and statistical error contributions to the top mass measurement expressed is m_t (GeV/c^2) for the 3 methods described in the text: the hadronic mass fit, the kinematic fit and the high p_T selection.

	had. top	kin. fit	high p_T
light jet E scale (1%)	0.2	0.2	-
b-jet E scale (1%)	0.7	0.7	-
b-quark fragmentation	0.1	0.1	0.3
ISR	0.1	0.1	0.1
FSR	1.0	0.5	0.1
combinatorial bkg	0.1	0.1	-
mass rescaling	-	-	0.9
Underlying event (10%)	-	-	1.3
total syst.	1.3	0.9	1.6
stat. err. @ 10 fb^{-1}	0.05	0.1	0.2

Already with 10 fb^{-1} of data, flavour changing neutral currents, which are not allowed at tree level in the SM, can be observed with a sensitivity 2 orders of magnitude better than at Tevatron [6,7]. Finally by studying the double differential angular distribution of $t\bar{t}$ decay products and by comparing the observed values of the spin correlation observables and the SM expectations, the presence of anomalous couplings, Technicolor, spin 0/2 heavy resonances can be observed. With an integrated luminosity of 10 fb^{-1}, the spin correlation observables can be extracted with a 3% and 5% statistical and systematical uncertainty, respectively [8,9].

6 Conclusions

Top physics provides an excellent environment for calibrating the detector and for testing the SM predictions as well as new physics starting from the early days of data taking at the LHC. A large effort has been made by the ATLAS and CMS Collaborations to be ready to analyse the top events from day one, by searching for better selection cuts, improving the generators and systematic errors understanding and exploring alternative analysis methods and decay channels.

References

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