PROCEEDINGS OF SCIENCE

Single top production at the LHC

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Electroweak production of single top quarks opens the possibility to extract precise information on the Wtb coupling at LHC. It is expected that all three different Standard Model modes of single-top production will be observed individually at LHC. Recent studies of ATLAS and CMS on this subject are described.

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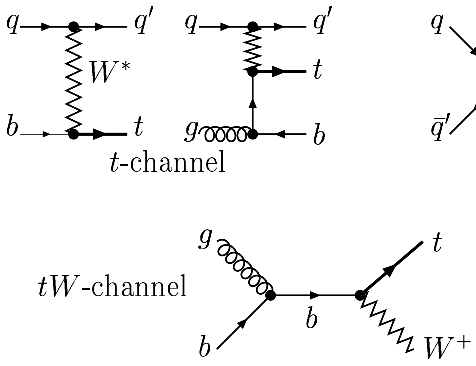

Figure 1: Lowest order Feynman diagrams for single top production.

1. Introduction

In the Standard Model (SM), three production modes are available for single top events, distinguished by the virtuality of the W boson coupled to the top (Fig. 1).

At the time of this publication no experimental evidence exists for single top, but the exclusion limits from the Tevatron experiments are fastly approaching the expectations for s-channel and t-channel cross sections in the SM framework, and the observation of these processes is expected before the closure of the accelerator. LHC will provide much higher statistics for all the three channels, allowing the observation also of the Wt production mode, and a more precise study of the single top phenomenology.

The study of single top production provides a unique possibility to investigate some aspects of top quark physics that cannot be studied in $t\bar{t}$ production. In particular,

- the only way to measure directly V_{tb} (CKM matrix element)
- investigation of the tWb vertex structure and FCNC $tu(c)g$ coupling directly in the production processes
- search for possible manifestation of New Physics beyond SM, such as anomalous couplings and s-channel resonances like W'-bosons.

Moreover, the single top quark production presents an irreducible background to several searches for Standard Model and New Physics signals (for example Higgs boson searches in the associated production channel) and may provide additional measurements of the top quark mass and of the top quark spin, supplementary to the top pair channel.

The electroweak single-top-quark production rate at the LHC is also calculated in the SM to the NLO level of accuracy for all three production mechanisms. The computed NLO cross sections are 152.6 pb and 90.0 pb for the t-channel t and $\bar{t}$ production respectively [1], and 6.55 pb and 4.07 pb for the s-channel t and $\bar{t}$ [2, 3]. For the associated W production channel, the cross sections for t and $\bar{t}$ production are the same, giving for $W^- t + W^+ \bar{t}$ about 60 pb [4, 5].

Concerning the main backgrounds, NLO computations [6] including the re-summation of the Sudakov logarithms (NLL) [7] lead to the top pair production cross section of about 830 pb, while LO estimations of the $Wb\bar{b}$ background yield a cross section of ≈ 300 pb (see Ref. [8]).

The three single-top processes result in quite distinct final states, leading to the definition of specific analyses in each case, making use of differences in jet multiplicity, number of b-tagged jets required, as well as angular distributions between lepton and/or jets present in the final states. Besides, important differences subsist in the level of backgrounds that are faced in the various analyses, leading to the development of tools dedicated to the rejection of specific backgrounds.

In the following sections, the selection strategies for the three production modes will be described separately. The results of some recent ATLAS and CMS studies will be shown. (CMS analyses are in progress and will be completed with the publication of the CMS Physics Technical Design Report, Volume II).

2. t-channel

As shown by Fig. 2 the final partons (*b*-quark from top-quark decay, the charged lepton and light quark) have relatively large transverse momenta. However, an additional *b*-quark is produced with small transverse momentum. This will make very difficult to identify the low p_T jet originating from this quark and tag it as *b*-jet. Another specific feature of the t-channel single top events is the production of a light jet in the forward/backward direction (see Figs. 3).

Therefore, most analyses for this channel select exactly two energetic jets, one anti-*b*-tagged and with high $|\eta|$ ("forward region"), the other *b*-tagged (since it has to come from the top decay $t \to Wb$) in the "central region", plus an energetic lepton and some missing transverse energy due to the leptonic decay of the W. Fully hadronic decays of the top are not considered, since the low jet multiplicity would make the separation from the QCD backgrounds unfeasible (it is very challenging even for the fully hadronic decays of $t\bar{t}$ pairs, in spite of their higher jet multiplicity).

It has to be noted that the choice of leptonic W decays leads to some difficulties when trying to reconstruct the top, since the neutrino is unobserved and one has to rely on the missing energy measurement in order to reconstruct its 4-momentum, as will be described later in this section.

The missing energy resolution is limited by the intrinsic resolution of the calorimeters, by their non-hermeticity, by the additional smearing due to pile-up, and by the fact that other processes provide additional missing energy to the event (e.g. $\pi \to \mu\nu$, $K \to \mu\nu$). Moreover, in a hadron collider the initial partons partecipating in the hard interaction are not constrained to have the same momenta, so the hard event are balanced only in the transverse plane. So, only the transverse missing energy ($\not{E}_{\mathrm{T}}$) is considered, and attributed to the neutrino from W decay, and the longitudinal component of the neutrino momentum is extracted by imposing the W mass as constraint. This is done by solving the quadratic equation:

$$M_W^2 = 2\left(E_\mu\sqrt{P_{z,\nu}^2 + \not{E}_{\mathrm{T}}^2} - \vec{P}_{T,\mu}\cdot\vec{\not{E}}_{\mathrm{T}} - P_{z,\mu}P_{z,\nu}\right) \tag{2.1}$$

This equation has two solutions:

$$P_{z,\nu}^{(1,2)} = \frac{AP_{z,\mu} \pm \sqrt{\Delta}}{P_{T,\mu}^2} \tag{2.2}$$

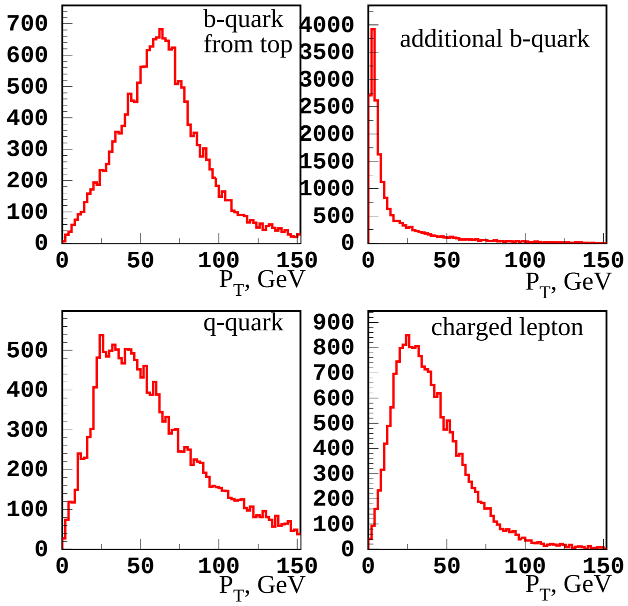

Figure 2: Transverse momentum distributions of the final *b*-quarks, the light forward quark and charged lepton at the partonic level in signal events generated with SingleTop [9].

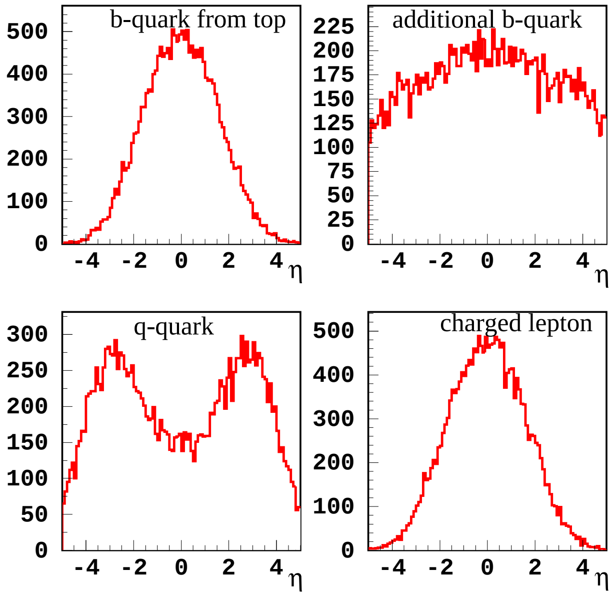

Figure 3: Pseudorapidity distributions of the final *b*-quarks, the light forward quark and charged lepton at the partonic level in signal events generated with SingleTop [9].

where

$$A = \frac{M_W^2}{2} + \vec{P}_{T,\mu} \cdot \vec{\not{E}}_{\mathrm{T}}, \quad \Delta = E_\mu^2 (A^2 - \not{E}_{\mathrm{T}}^2 P_{T,\mu}^2).$$

As anticipated, two difficulties are present:

- the problem has a two-fold ambiguity, due to the fact that the mass constraint is a quadratic equation;
- in a non-negligible fraction of the events, no real solutions are present (i.e. $\Delta < 0$), due to the resolution effects on $\not{E}_\mathrm{T}$ discussed above.

A further selection is done by reconstructing the top and taking a mass window around the nominal mass. The ATLAS analysis chooses to simply discard the events with no real solution, and among the two real solutions the one giving the combination $l\nu b$ with invariant mass closest to the nominal top mass is taken. The CMS analysis, still ongoing at the time of this publication, chooses instead to recover those events (whose compatibility with the hypothesis of a leptonically decaying W is required by cutting on the transverse mass around the "Jacobian peak"). This is done by treating M_W as a free parameter, and increasing him until Δ becomes non-negative(i.e. $\Delta = 0$); then, using this new value of M_W, $P_{z,\nu}$ is calculated from Eq. 2.3. When two real solutions are present, the one with minimum $|P_{z,\nu}|$ is used for the W-boson momentum reconstruction.

The ATLAS analysis shows that with the above strategy they foresee to select 7000 signal events with an integrated luminosity of 30 fb^{-1}, with a signal to background ratio of around 3, the main backgrounds being W+jets and top pairs. The statistical error is expected to be $\sqrt{S+B}/B =$ 1.4% (30 fb^{-1}).

3. s-channel

The study of single top production via the s-channel process $q\overline{q'} \to W^* \to t\overline{b}$ $(\overline{t}b)$ gives a complementary measurement of the $|V_{tb}|$ CKM matrix element with respect to the t-channel mode, due to the completely different initial state. This involves only u $(\overline{u})$ and d $(\overline{d})$ quarks, whose PDF's are the best known, while the t-channel and Wt associated productions include the less known gluon and b $(\overline{b})$ quark PDF's. Moreover, it is in principle possible to extract $|V_{tb}|$ from the ratio $\sigma(q\overline{q'} \to W^* \to t\overline{b}\ (\overline{t}b))/\sigma(q\overline{q'} \to W \to \mu\nu)$, which cancels some theoretical uncertainties[1].

An additional reason of interest on the s-channel production cross section is its sensitivity to the existence of additional bosons, e.g. Kaluza Klein excitations of the W or high mass $H^\pm$ [10].

In ATLAS and CMS, a first selection is applied with the following criteria:

- the event must have at least one high-p_T lepton in the central region;
- a possible second lepton is vetoed if his p_T exceeds 10 GeV (in order to allow only the relatively soft leptons from b decay chains, and reject most of the events in which two W's are present and both decay leptonically, like in $t\overline{t} \to l^+\nu b l^-\overline{\nu}\overline{b}$);
- a cut is applied on the transverse missing energy, in order to reject backgrounds with no W in the final state;
- the event must have exactly two high-p_T jets (a veto is defined for any third jet above a p_T threshold), in order to reduce the top pair contamination on one side, and QCD and W+jets events on the other;

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[1] Of course this will require some care, since the selection cuts may introduce a dependence in the ratio if they select different phase spaces for the tb and the $\mu\nu$ systems.

- both jet have to be b-tagged; this is crucial to reduce the contamination of W+jets events.

It has to be noted that in this case there is a further ambiguity in the top reconstruction, apart from the one on the neutrino solution (as in the case of t-channel searches, discussed in the previous section), arising from the presence of two b-tagged jets in the final state. The ATLAS analysis takes, of the four possible combinations of neutrino solutions and b-jet choice, the one giving the maximum p_T for the reconstructed top. The CMS analysis, yet unpublished, chooses the neutrino solution with minimum $|P_{z,\nu}|$ and the b-jet is chosen according to the sign of the "jet charge" (Q_j), defined as the sum of the charges of the tracks inside the jet cone, weighted over the projections of the track momenta along the jet axis: if the two jets have opposite signs of Q_j, the top candidate is formed with the one opposite to the lepton charge; otherwise, the one giving the highest p_T of the reconstructed top is chosen.

In ATLAS, further selection is made using the reconstructed top mass $M(l\nu b)$ (Fig. 4) and H_T, defined as $E_T^l + \not{E}_T + \Sigma_{jet}\, E_T^{jet}$ (Fig. 5). These variables are used also in the CMS selection, where moreover an additional S/B enhancement is obtained by cutting on Σ_T (defined as the vectorial sum in the transverse plane of the momenta of the lepton, of $\not{E}_T$ and of the two b-jets, Fig. 6) and the invariant mass of the tb system (Fig. 7); both variables are in fact expected to have smaller values, on average, for s-channel single top events than for t-channel and $t\bar{t}$.

In the ATLAS analysis about 1,200 (840) signal events are expected in the $t\bar{b}$ ($\bar{t}b$) final states, after 30 fb^{-1} of data, for a S/B ratio around 10%. The dominant background comes from the top pair production in the dilepton and lepton+jets channels, followed by the $WQ\bar{Q}$ ($Q = c, b$) contamination. The remaining W+jets contamination is due to the high cross section for such events, and is expected at this stage to be slightly above the signal expectation.

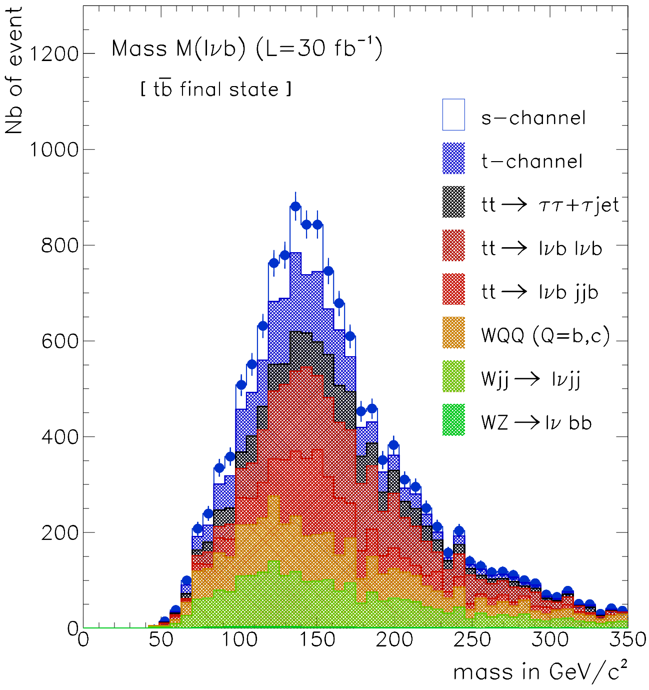

Figure 4: Distribution of reconstructed top mass for 30 fb^{-1} in ATLAS.

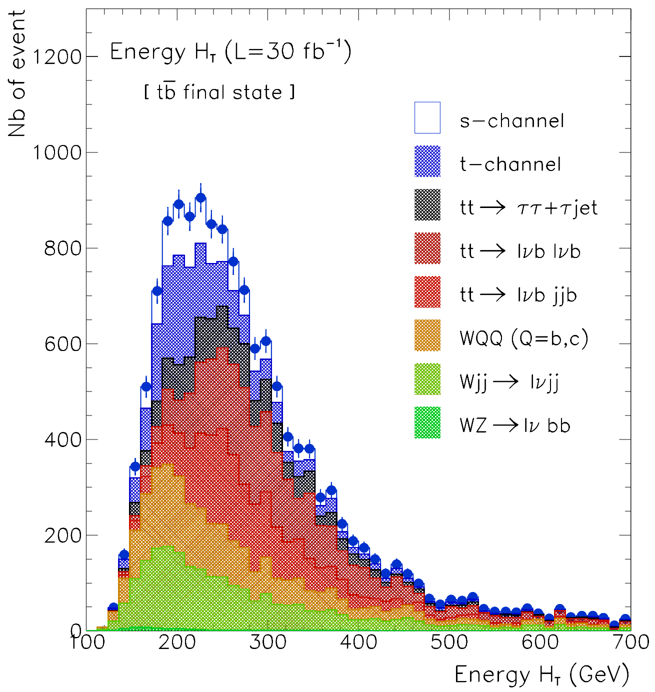

Figure 5: Distribution of H_T for 30 fb^{-1} in ATLAS.

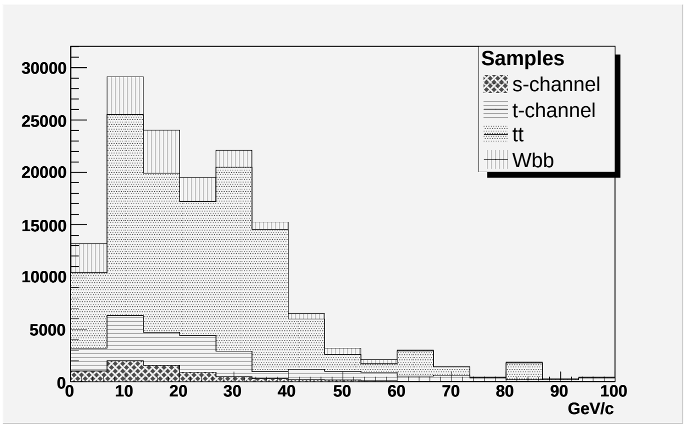

Figure 6: Distribution of Σ_T (after preselection) for 10 fb^{-1} in CMS.

Among the main sources of systematic uncertainties are the jet energy scale, the b-tagging efficiency and mistag rate, and the modelling of Initial State Radiation (ISR) and Final State Radiation (FSR) effects. These sources affect the signal as well as the background selection efficiencies.

Uncertainty in the jet energy scale affects the selection efficiencies directly, via the jet p_T thresholds and the veto on the third jet, and indirectly via the missing energy, H_T and reconstructed top mass cuts. The imperfect knowledge of the b-tagging efficiency and mistag rates affects the background rejection. ISR and FSR have a dramatic influence on the jet multiplicity, and FSR has also an effect on the jet energy scale.

ATLAS performed a detailed study of the systematic effects, and optimized the analysis in

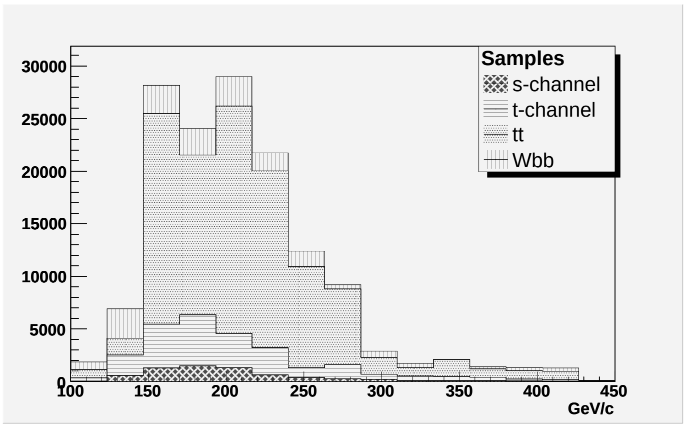

Figure 7: Distribution of invariant mass of the tb system (after preselection) for 10 fb^{-1} in CMS.

such a way to minimize the overall error (statistics + systematics). After 30 fb^{-1} of integrated luminosity they expect, with their selection, a statistical error of 9%, an error of 3.4% due to the expected uncertainty on jet energy scale, a 6.4% error due to b-tag efficiency and mistagging, and a preliminary estimation of the impact of ISR/FSR modelling on the analysis yields a 7.3% uncertainty. This latest number has to be considered as conservative, since it is obtained by switching off the radiation and by taking 10% of the observed shift in selection efficiency as systematic. A more realistic estimation is ongoing and will be published soon.

The luminosity uncertainty is expected to be around 5% [11]. The current theoretical uncertainties on the background total cross sections is shown to affect the ATLAS analysis with a 8.0% systematic contribution, so estimating them from data will be of paramount importance.

These numbers show that this analysis is dominated by systematic uncertainties.

4. Wt

From the theoretical point of view the definition of the Wt signal is not trivial, since at NLO it mixes with $t\overline{t}$; see for example [5] for a discussion and a proposed MC-friendly solution to this problem.

ATLAS has chosen a lepton+jets strategy: one high-p_T lepton and exactly three jets (one b-tagged) are requested. Further selection is done by selecting a mass window around M_W for the two non b-tagged jets, and around M_t for the $l\nu b$ system (assuming that the leptonically decaying W is the one from top) and cutting on H_T. After this selection, the sample is dominated by $t\bar{t}$ events, in a $7:1$ ratio to the signal, with very small contributions from other backgrounds.

For an integrated luminosity of 30 fb^{-1} ATLAS expects 4700 events (i.e. an efficiency of the order of 1%), resulting in a statistical sensitivity of about 4%. A large systematic error is expected to come from the jet energy scale and from ISR/FSR modelling.

5. Conclusions

The Tevatron experiments are expected to observe single top quark events before 2009, but precise measurements of all the three production modes will only be possible with the higher energy and luminosity provided by LHC.

The measurement of all three processes will provide a precious test of the electroweak model in the top sector, which in turn will allow the first direct determination of $|V_{tb}|$, and a probe to new physics.

6. Acknowledgements

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