SN-ATLAS-2001-007
4 Dec 2001

Prospects for Measuring V_{tb} via s-channel Single Top at ATLAS

Dugan O'Neil [a,c], Beatriz González Piñeiro [b], and Michel Lefebvre [a]

a Department of Physics and Astronomy, University of Victoria Box 3055, Victoria, B.C., Canada

b Department of Physics and Astronomy, Michigan State University East Lansing, MI 48824, USA

c current address: Department of Physics and Astronomy, Michigan State University East Lansing, MI 48824, USA

Abstract

The production of single top quarks via the electroweak interaction promises to provide new opportunities to both test the Standard Model and search for new physics. In particular, electroweak top production provides the only means to directly measure the CKM matrix element V_{tb} at ATLAS. The s-channel has the lowest rate, but is the best theoretically understood mechanism of electroweak top production. An evaluation of the potential for background suppression and V_{tb} measurement in this channel is presented. It is found that significant background suppression can be achieved and V_{tb} can be measured in the s-channel to a statistical precision of 2.8% after 3 years of low luminosity data taking (3×10^4 pb^{-1}) at the LHC.

1 Introduction

To date the only observed mechanism for top quark production is $t\bar{t}$ pair-production via the strong interaction. The production of single top quarks via electroweak interactions has yet to be observed, but promises to provide new opportunities to both test the Standard Model and search for new physics. At the Large Hadron Collider (LHC) [1], the predicted cross-sections for such processes are high, making it an excellent laboratory in which to perform single top studies.

There are three major diagrams for single top production at the LHC. These diagrams along with their major backgrounds are shown in Figure 1. The dominant single top production mechanism is t-channel production (Wg-fusion) followed by associated production (Wt) and then by s-channel (W^*) production. A detailed discussion of cross-sections will be presented in Section 3.

This note considers the possibility of isolating the s-channel (W^*) single top production channel in order to measure its cross-section and extract a value of $V_{\rm tb}$. Compared to other single top channels, the s-channel benefits from lower theoretical uncertainties in its cross-section but suffers from a low production rate. Isolating it from its backgrounds is a significant challenge. Previous studies [3] of single top production have chosen not to treat the s-channel process at the LHC due to these background considerations.

The second section describes the theoretical motivation for the study. Section 3 discusses the Monte Carlo generators used for each process and the overall cross-section normalization applied to each signal. Section 4 focuses on kinematic distributions of signal and background. Section 5 treats the results obtained in signal-to-background (S/B) optimization and $V_{\rm tb}$ measurement obtained in the s-channel. Section 6 discusses sources of error in the cross-section determination. Finally, Section 7 presents the conclusions.

2 Motivation

Electroweak top production provides the best opportunity to measure the properties of the W-t-b vertex at the LHC. Given existing measurements, the Standard Model provides precise predictions for the CKM matrix element $V_{\rm tb}$ and for the polarization of the electroweak top sample. The s-channel single top signal provides a sample of highly polarized [4] top quarks with rate proportional to $|V_{\rm tb}|^2$. This work focuses on the measurement of the cross-section of the s-channel process and the extraction of the value of $V_{\rm tb}$ from this measurement.

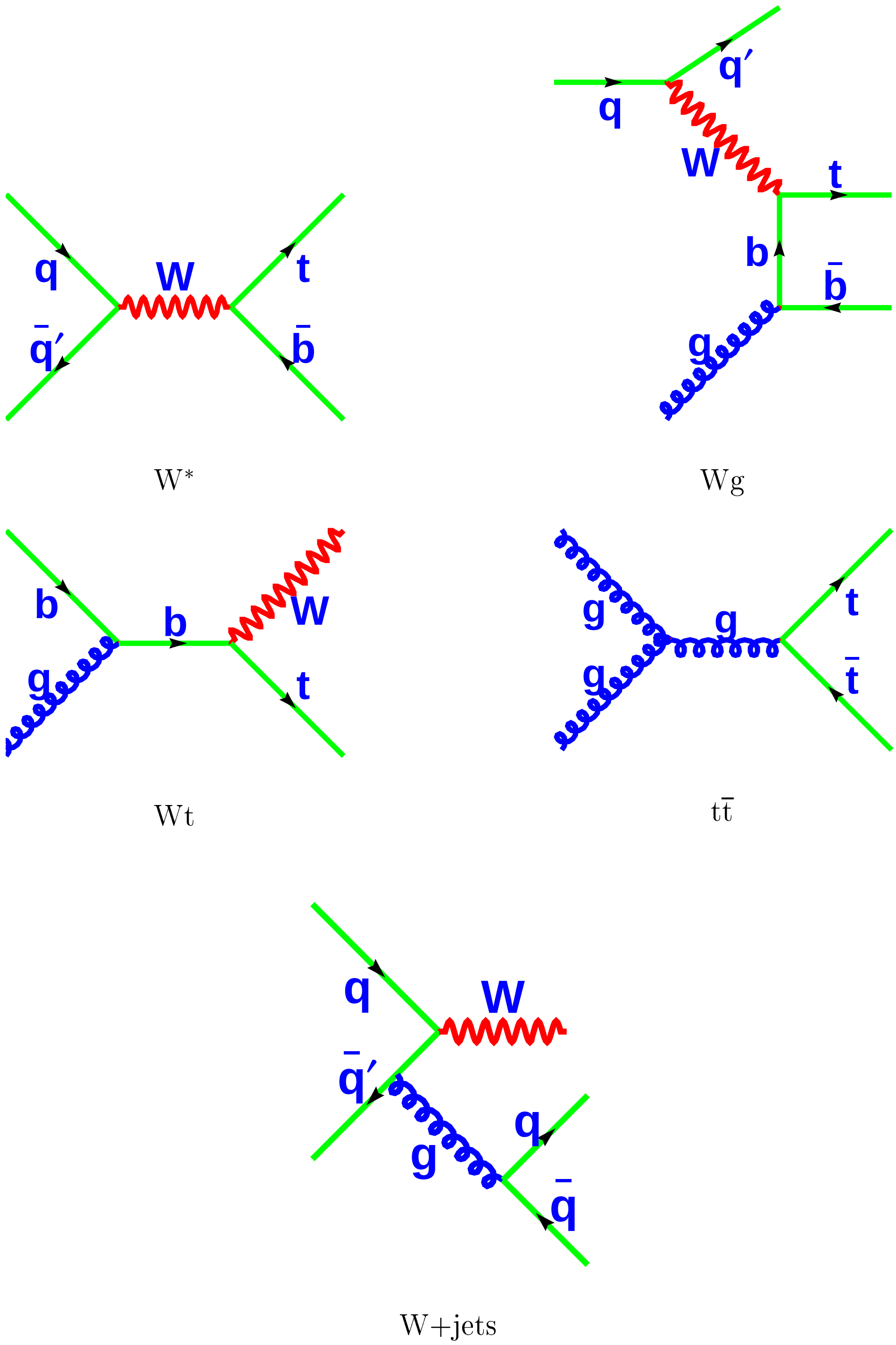

Figure 1: *Single top signals and background at the LHC. Reading from left to right, top to bottom the diagrams are W*, Wg-fusion, Wt, and backgrounds* $t\bar{t}$ *and W+jets.*

The value of the CKM matrix element $V_{\rm tb}$ has never been directly measured. Despite this fact it is, as a fraction of its value, the most highly constrained element of the matrix [5,6]. This value for $V_{\rm tb}$ relies on a unitarity constraint which assumes three quark generations (ie. $|V_{\rm td}|^2 + |V_{\rm ts}|^2 + |V_{\rm tb}|^2 = 1$). If this assumption is invalid the value of $V_{\rm tb}$ is virtually unconstrained. A measurement of $V_{\rm tb}$ different from the predicted value would imply the existence of physics beyond the Standard Model. For example, if the s-channel single top measurement of $V_{\rm tb}$ is larger than predicted by the Standard Model it could imply the existence of a heavy vector boson (W′).

There are several ways to obtain indirect information on $V_{\rm tb}$. The dominant mechanism for producing top quarks at the LHC is $\rm t\bar{t}$ production. Though this source of top quarks contains two W-t-b vertices in its decay it cannot be used to make a direct measurement of $V_{\rm tb}$. Measurements from $\rm t\bar{t}$ can provide a ratio of matrix elements

$$\frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{\rm tb}|^2}{|V_{\rm td}|^2 + |V_{\rm ts}|^2 + |V_{\rm tb}|^2}$$

and hence can constrain $V_{\rm tb}$ in a 3-generation model (see CDF measurement [7]), but cannot be used to extract $V_{\rm tb}$ directly. $V_{\rm tb}$ can also be constrained by comparing precision electroweak measurements to loop corrections containing the W-t-b vertex.

Electroweak top production is the only way to produce a direct measurement of $V_{\rm tb}$ at a hadron collider. Each single top process has a cross-section which is directly proportional to $|V_{\rm tb}|^2$. By measuring the rate of single top processes and combining this information with the value of the t→Wb branching ratio and top mass measurements from the $\rm t\bar{t}$ channel, the absolute value of $V_{\rm tb}$ can be extracted.

Different production diagrams have different advantages for measuring $V_{\rm tb}$. For example, the Wg-fusion process has a very high rate at the LHC leading to a high statistical precision in that channel. The major advantage to studying single top in the s-channel is that the theoretical errors in this channel are well understood. Table 1 shows the sources and levels of theoretical error in Wg-fusion and s-channel single top production. This table illustrates the advantage of the s-channel. Since its cross-section calculation does not rely on gluon parton density functions (pdf) the errors due to pdf uncertainty are significantly lower than for Wg-fusion. The error on the cross-section due to an assumed 2 GeV error on the top mass is higher for W^* than for Wg-fusion, but this is outweighed by the advantage in the other sources of error. Another theoretical advantage of W^* is that its sources of error can be studied with high statistics at the LHC using Drell-Yan W production, a very similar process.

Source	W^*	Wg
pdf	4%	10%
μ (scale)	4%	10%
ΔM_t	5%	3%

Table 1: *Sources and levels of theoretical error in the cross-sections of Wg and W^*. The error due to imprecision in the mass of the top is calculated assuming the mass is known to 2 GeV (expected from LHC measurements). In this table pdf refers to the error calculated by choosing different parton density function sets. The μ (scale) refers to the error obtained by varying the renormalization scale at which the calculation is performed [8]. The error in the gluon pdf is from [9], all other numbers are taken from [10].*

3 Generators and Cross-sections

Single top production at the LHC is plagued by several high rate backgrounds including $t\bar{t}$ and W+jets production. These backgrounds are particularly difficult in the W^* channel for which the other single top channels are also serious backgrounds. The cross-sections for the processes of interest are shown in Table 2 for 175 GeV top quarks. The column of $\sigma \times$BR assumes that only top decays to electrons or muons are measured as these are the only final states considered in this study. This table illustrates the size of the backgrounds relative to the W^* signal. The rate of non-top backgrounds is almost 2000 times the rate of s-channel single top. The $t\bar{t}$ background has a rate almost 100 times larger than the s-channel single top and the other single top channels have a combined rate which is more than 30 times that of the s-channel. The W^*, Wg-fusion and $t\bar{t}$ cross-section predictions come from analytic next-to-leading-order calculations. The cross-sections for Wt, W+jets and $Wb\bar{b}$ come from Monte Carlo calculations with leading-order matrix elements.

In this study all of the processes containing top quarks were generated using the ONETOP [16] generator. This is a parton-level leading-order generator which keeps all helicity information and hence produces the correct angular distributions of top decay products. The particles from ONETOP were then passed to PYTHIA [17] which fragmented the final state particles, added initial and final state radiation and simulated the underlying event. Finally events were passed into ATLFAST version 1.61 [18] in order to apply ATLAS-like detector smearing effects.

The non-top backgrounds considered in this study were generated using HERWIG and were also passed through ATLFAST version 1.61. The $Wb\bar{b}$ background was generated using non-standard HERWIG code which interfaces the $Wb\bar{b}$ matrix element from reference [19] to HERWIG. The W+jets process is a standard HERWIG process. Since the

process	generator	total cross-section (pb)	$\sigma\times$ BR (pb)
W*	ONETOP	10 [11]	2.22
Wg-fusion	ONETOP	244 [12]	54.2
Wt	ONETOP	60	17.8
$\mathrm{t\bar{t}}$	ONETOP	830 [13]	246
$\mathrm{Wb\bar{b}}$	M.E + HERWIG	300 [3]	66.7
W+jets	HERWIG	18000	4000

Table 2: *Cross-sections for the processes considered in this study and the cross-section × branching ratio needed for only electron and muon final states. The cross-section for the W+jets process is obtained by normalizing the cross-section obtained from HERWIG [14] with cuts requiring at least 2 jets above 15 GeV with $|\eta| < 3.2$ to the cross-section from VECBOS [15] for these cuts. HERWIG is then used to estimate the cross-section when the jet region is extended to $|\eta| < 5$ to obtain 18000 pb. The generator for the* $\mathrm{Wb\bar{b}}$ *process is the combination of a matrix element from [19] and HERWIG.*

quark jets in the W+jets process are assumed to be massless, the cross-section for this process becomes infinite at low jet transverse momentum (collinear divergence). To avoid this problem the cross-section for this process was defined only when 2 jets above 15 GeV P_{T} were found within the pseudo-rapidity range $|\eta| < 5$ using the standard ATLFAST cone-based jet finding algorithm ($\Delta R = 0.4$). The cross-section has been normalized using the value from the VECBOS [15] Monte Carlo generator.

4 Comparison of Kinematics in Signal and Background

In order to understand the differences between the W* signal and its major backgrounds it is necessary to compare a variety of kinematic variables. Distributions of several useful variables are presented in this section. Each distribution has been normalized to unit area in order to emphasize kinematic rather than rate differences. All of the plots displayed herein are created after ATLFAST and ATLFAST-B[1] have been used to smear the distributions. All observables must meet their default definition in ATLFAST. In ATLFAST-1.61 these defaults for electrons, jets and b-jets are:

- isolated electrons: $|\eta| < 2.5, P_{\mathrm{T}} > 5$ GeV, separation of $\Delta R > 0.4$ from other clusters and $E_{\mathrm{T}} < 10$ GeV in an ΔR =0.2 cone, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

[1]ATLFAST-B is a set of routines to simulate efficiencies for tagging b-jets, tau-jets and c-jets. These routines also provide jet-energy calibration.

- jet: $|\eta| < 5, P_T > 15$ GeV;
- b-jet: jet and $|\eta| < 2.5$, 60% tagging efficiency, 10% c-mistag rate and 1% light-quark mistag rate.

Pre-selection cuts have also been applied before the distributions in this section were created. These cuts should mimic the effect of a single top trigger selection. The cuts used are:

- at least 1 b-jet above 50 GeV P_T ;
- at least 1 lepton above 20 GeV P_T ;
- at least 2 jets above 30 GeV P_T .

The first variable of interest is the number of jets in the event. Figure 2 shows the number of reconstructed jets in an event for the W^* signal and each of its backgrounds. These distributions clearly illustrate that, on average, $t\bar{t}$ events produce more jets than W^* events. A cut requiring the presence of exactly 2 jets in each event is a major rejector of the $t\bar{t}$ background.

The second kinematic variable considered here is the number of b-jets tagged in an event, presented in Figure 3. As mentioned previously, in this sample of events there is already a requirement that there be at least one tagged b-jet (hence the absence of events in the zero-jet bin). It can be seen from this figure that requiring more than one b-tagged jet will further enhance the W^* signal with respect to W+jets and Wg-fusion. Though in principle Wg-fusion events contain as many b-jets as W^* events, in practice one of the jets will quite often be missed (ie. not tagged) because it has low transverse momentum and will not meet the minimum b-tag requirements.

Another variable which can be used to separate signal from background is the reconstructed top mass (since there is no top quark in the W+jets background). Figure 4 shows the top mass reconstructed by choosing the b-jet and the neutrino z-momentum which give the best top mass [2].

These distributions can help distinguish W^* signals from Wg-fusion as well as non-single-top backgrounds. Another kinematic variable which could prove useful in distinguishing signal from background is the scalar sum of the P_T of all of the jets in an event, $\sum^{\text{jets}} P_T$. Figure 5 illustrates the different $\sum^{\text{jets}} P_T$ distributions for each process. The $\sum^{\text{jets}} P_T$ in $t\bar{t}$ is much higher on average than for the signal while the W+jets background has quite low $\sum^{\text{jets}} P_T$.

[2] Since the only measure of the neutrino momentum is via the missing P_T a W-mass constraint is used to reconstruct the neutrino z-momentum within a 2-fold ambiguity. A choice of z-momentum must therefore be made in order to obtain the neutrino 4-vector.

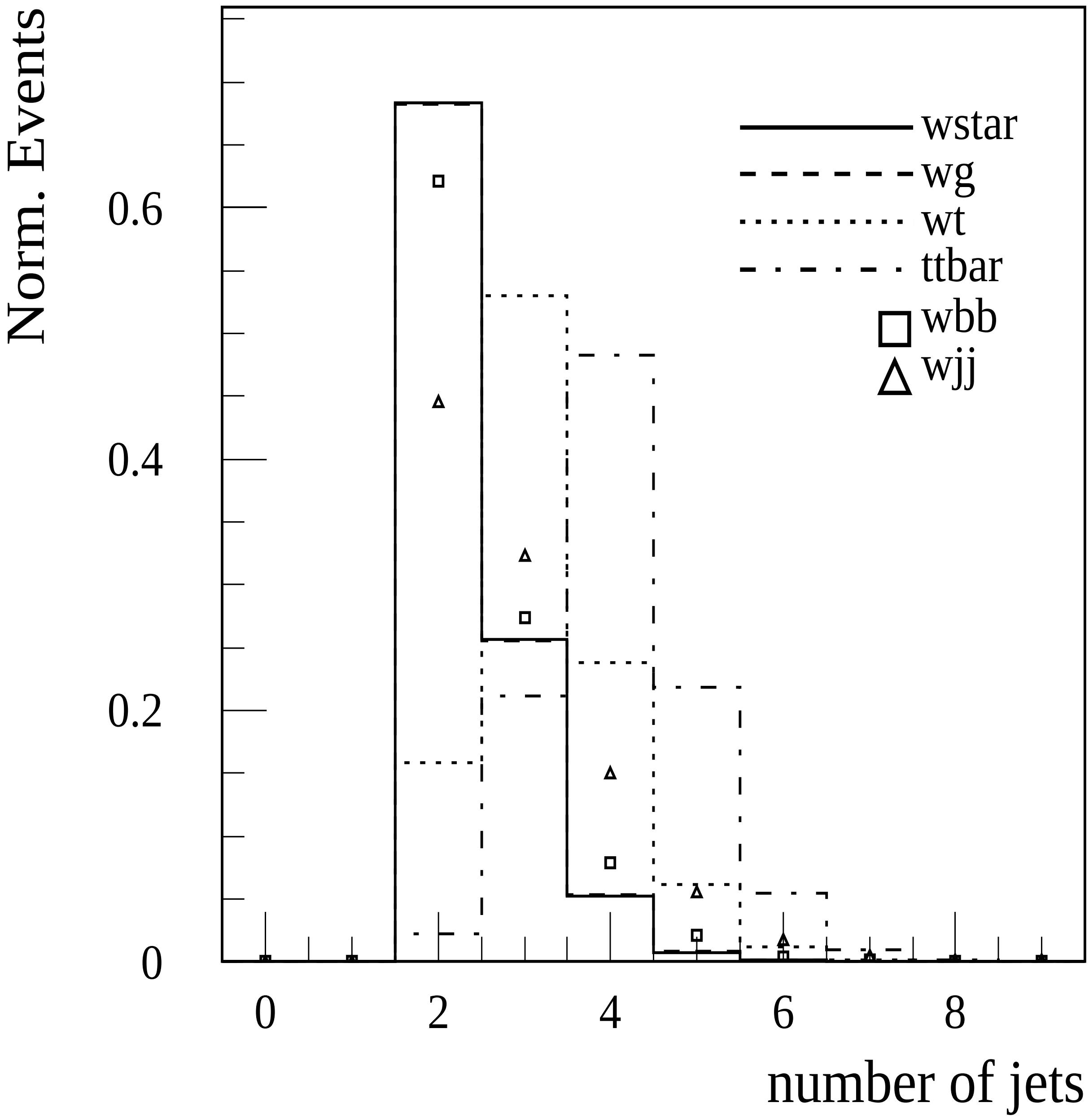

Figure 2: *Number of jets found in signal and background events after ATLFAST and ATLFAST-B. Refer to text for description of event pre-selection.*

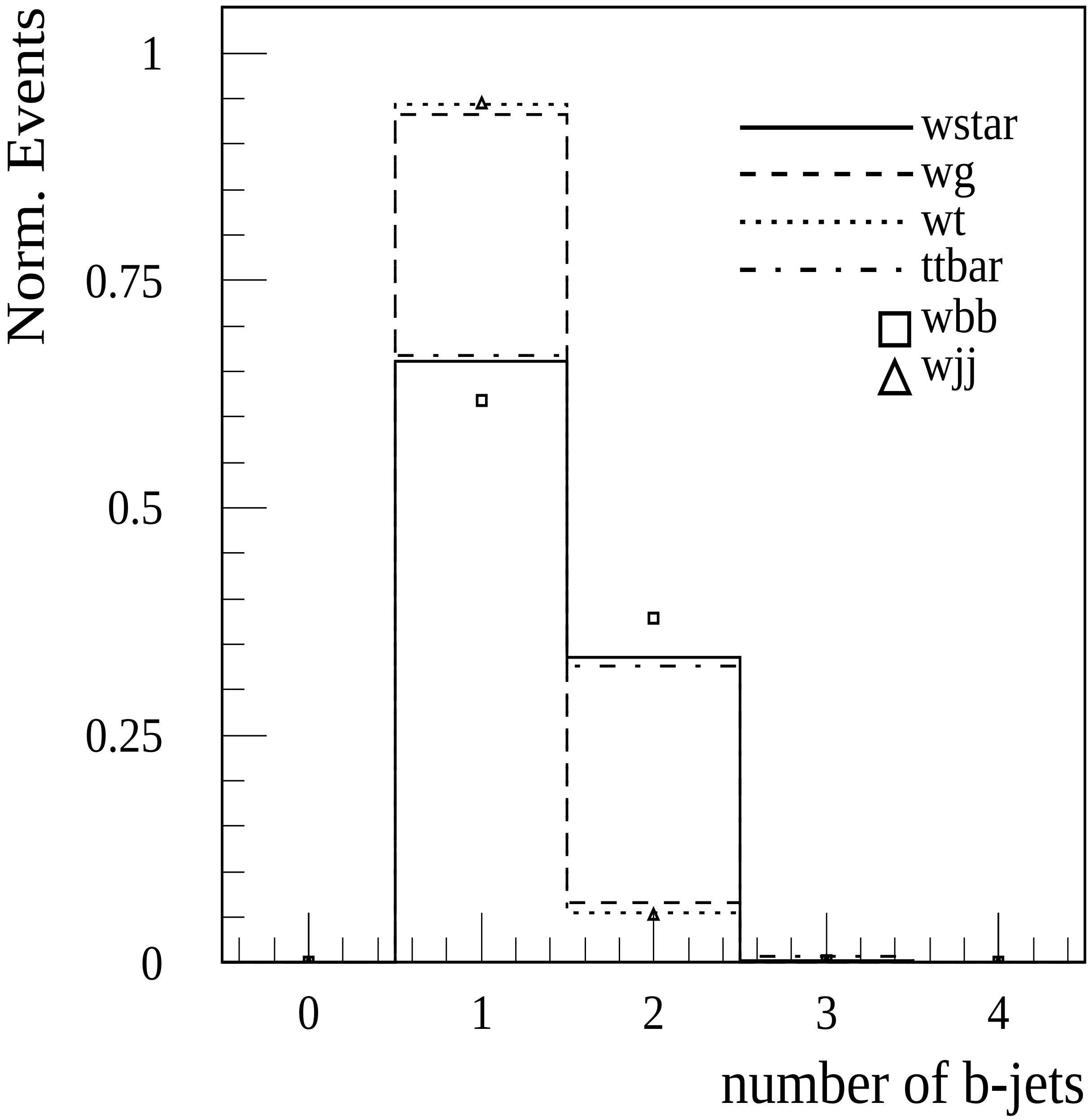

Figure 3: *Number of b-jets found in signal and background events after ATLFAST and ATLFAST-B. Refer to text for description of event pre-selection .*

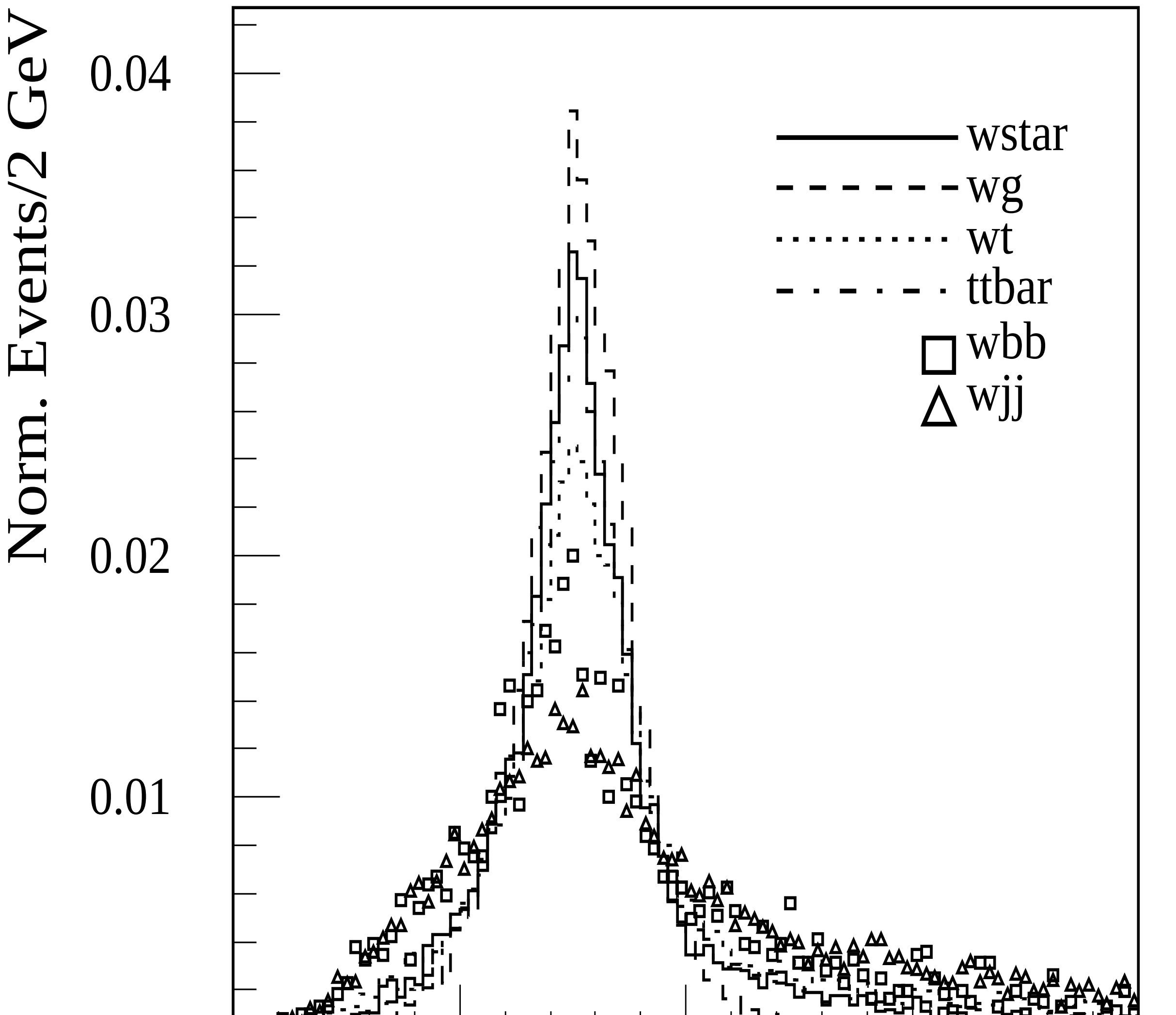

Figure 4: *l-b-ν combination that gives the best top mass. Refer to text for description of event pre-selection.*

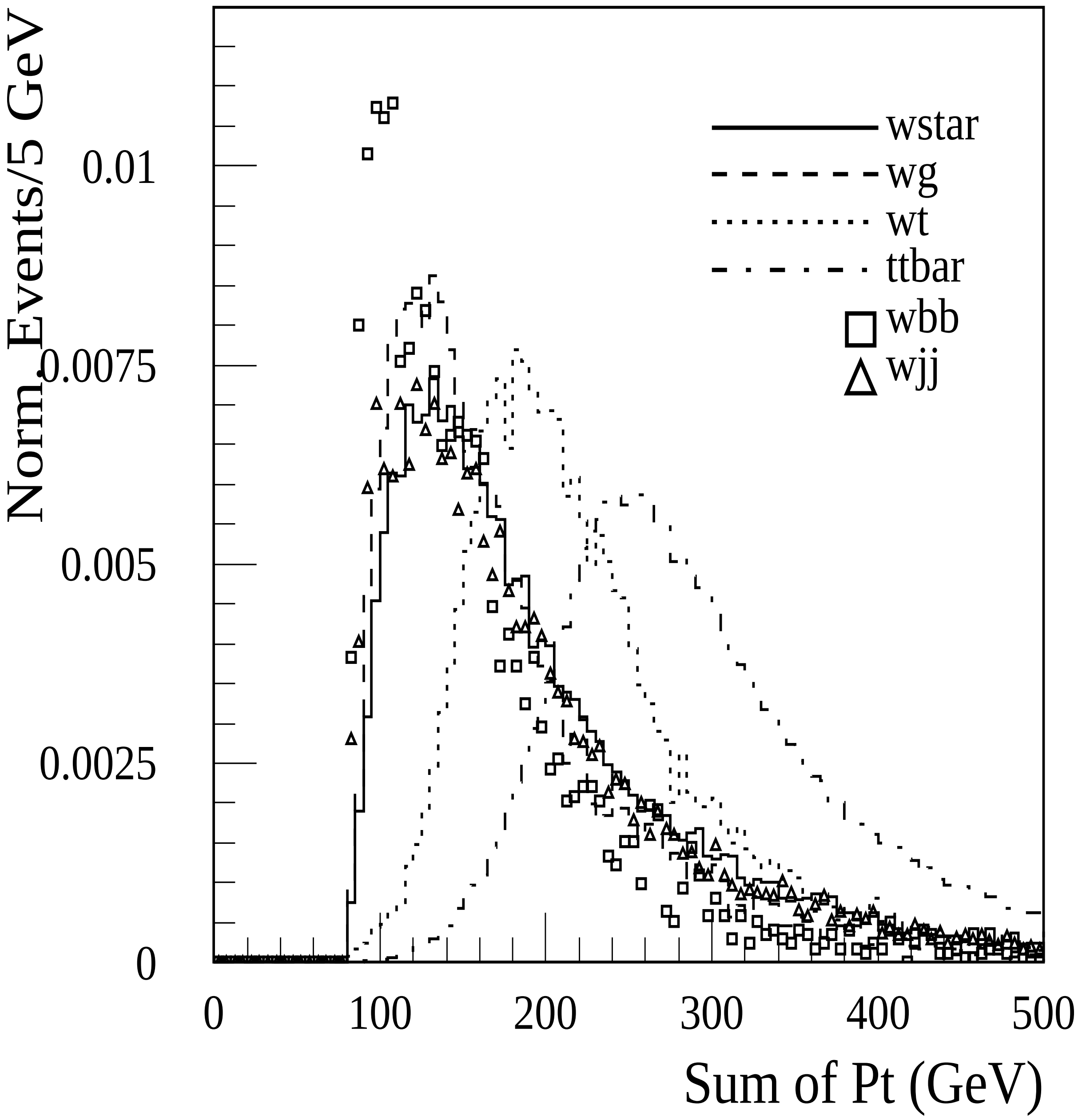

Figure 5: *Scalar sum of jet P_{T} in each event for signal and background after ATLFAST and ATLFAST-B. Refer to text for description of event pre-selection.*

5 Measurement of V_{tb} from W^*

5.1 Measurement Strategy

Since single top production in this channel proceeds directly through a W-t-b vertex, the cross-section is directly proportional to $|V_{\mathrm{tb}}|^2$. Therefore, in order to estimate the precision with which V_{tb} can be measured in the W^* channel it is necessary to estimate the precision with which the cross-section for this process can be measured.

The precision with which a cross-section can be measured is given by the fluctuation of the total number of events in the signal region, $S + B$ (where S=signal and B=background). Hence, under the assumption that the background cross-section is well known, it would appear that the best strategy for the measurement of the cross-section is one which minimizes the ratio $\sqrt{S+B}/S$, the fractional uncertainty in the cross-section. However, if B is expected to be comparable to or greater than S, the robustness of this strategy relies on a good knowledge of B, the background cross-section. In the case of W+jets and $\mathrm{Wb\bar{b}}$ production the cross-section at the LHC is not well known. For this reason, we have adopted a strategy that maximizes S/B . This ensures that our estimate of the fractional uncertainty on the signal cross-section, and hence on V_{tb} , is robust.

5.2 Kinematic Cuts to Optimize S/B

Since the W^* signal has such a small cross-section relative to its major backgrounds, obtaining a signal to background ratio close to (or better than) one is a challenge requiring stringent cuts. The following is a list of cuts designed to optimize S/B [3]:

1. the total number of jets is exactly 2
2. both jets are tagged as b-jets with $P_{\mathrm{T}} \geq 75$ GeV
3. scalar sum of jet $P_{\mathrm{T}} = \sum^{\mathrm{jets}} P_{\mathrm{T}} \geq 175$ GeV
4. reconstructed top mass in the range 150-200 GeV

The first cut, requiring exactly two jets in each event, is a strong cut rejecting $\mathrm{t\bar{t}}$ background. As illustrated in Figure 2, a very small percentage of $\mathrm{t\bar{t}}$ events contain only two jets, while it is the most frequent number of jets found in W^* single top events.

[3] Pre-selection cuts described in section 4 have already been applied.

The second cut makes strong demands on the b-jet content of the events. Each event is required to have exactly two b-jets with P_{T} greater than 75 GeV. A very small fraction of W+jets events are expected to contain 2 b-jets, while the other processes considered here will each contain at least 2 b-jets. Once detector effects have been taken into account (b-tagging efficiencies, etc.) this cut also becomes a good rejector of Wg-fusion events since the second (lower P_{T}) b-jet from these events tends to be very soft and is often lost outside the b-tagging region ($|\eta| < 2.5$). The second part of the cut (P_{T} of the b-jet) also acts to suppress Wg-fusion relative to W* by cutting on this second b-jet.

The scalar sum of the jet P_{T} in the event is a strong rejector of W+jets events since the total transverse momentum flow in these events is generally lower than for events containing top quarks.

The reconstructed top mass cut is used to reduce the W+jets and W$\mathrm{b\overline{b}}$ backgrounds, since these processes do not contain a top quark. Since the rest of the processes produce top quarks they are not strongly affected by this cut.

The combination of all of these cuts leads to the results presented in Table 3. This table lists the cumulative efficiency for each cut and the number of events expected after three years of LHC running at low luminosity (3×10^4 pb^{-1}). The errors quoted in the table are estimated using the square root of the number of Monte Carlo events remaining after cuts. Table 3 illustrates the challenge of isolating the W* signal. The stringent cuts required lead to a signal efficiency of less than 2%. These cuts designed to optimize S/B lead to a prediction for S/B of 0.55 and $S/\sqrt{B}$ of 22. Other combinations of cuts are possible which can give similar signal-to-background but generally at the expense of signal efficiency. For example, relaxing the jet multiplicity requirement to also accept events with more than 2 jets and re-optimizing the remainder of the cuts can lead to $S/B \sim$ 0.2-0.3, but at the cost of reducing signal efficiency by up to a factor of 5.

5.3 V_{tb} Results

After applying the kinematic cuts described in the previous section it is possible to estimate both the significance of the signal and the error on the cross-section measurement for W* at ATLAS after 3×10^4 pb^{-1}.

The quantity $\sqrt{S+B}/S$ can be used to estimate the fractional error in V_{tb} ($\Delta V_{\mathrm{tb}}/V_{\mathrm{tb}}$). From Table 3 the fractional uncertainty in the cross-section from statistical sources is calculated to be$\sqrt{S+B}/S = 5.6\%$, leading to a relative statistical error on V_{tb} of 2.8%. Assuming a 7.5% theoretical error in the cross-section (adding in quadrature the errors

cut	W^* eff(%)	Wg-fusion eff(%)	Wt eff(%)	$t\bar{t}$ eff(%)	$Wb\bar{b}$ eff(%)	W+jets eff (%)	S/B
Pre-selection	27.0	20.0	25.5	44.4	2.49	0.667	0.004
njets=2	18.4	13.7	4.03	0.996	1.55	0.297	0.017
nbjet=2 P_{T} >75 GeV	2.10	0.05	0.018	0.023	0.038	0.0005	0.35
$\sum^{\mathrm{jets}} P_{\mathrm{T}}$ >175 GeV	1.92	0.036	0.016	0.021	0.031	0.0004	0.38
$M_{l\nu b}$ 150-200 GeV	1.36	0.023	0.006	0.012	0.0097	0.00014	0.55

events/ 3×10^4 pb^{-1} (before cuts)	66600	1.63×10^6	534000	7.2×10^6	2.0×10^6	6.8×10^7	.0008
events/ 3×10^4 pb^{-1} (after cuts)	908 $\pm$35	375 $\pm$13	32 $\pm$18	885 $\pm$181	194 $\pm$34	169 $\pm$76	0.55 $\pm$0.14

Table 3: *Cumulative effect of cuts on W^* signal and backgrounds. The first 5 rows of this table refer to cumulative efficiencies of various cuts. The last two rows refer to the number of events for 3×10^4 pb^{-1}. Only events in which the $W\rightarrow e\nu$ or $\mu\nu$ are considered in this table. Errors quoted in this table are due entirely to Monte Carlo statistics.*

from Table 1) and combining the theoretical error in quadrature with the statistical error quoted above yields

$$\frac{\Delta V_{\rm tb}}{V_{\rm tb}} = 4.7\%$$

It is noteworthy that at this time the predicted error on this measurement would be dominated by theoretical error on the cross-section.

6 Sources of Error

Theoretical errors on single top production cross-section calculations have already been discussed in Section 2. In addition to the sensitivity of the $V_{\rm tb}$ measurement to errors in the single top cross-section, it is also sensitive to errors in the cross-sections of the backgrounds. In particular, the cross-section for the W+jets and $\rm Wb\overline{b}$ processes at the LHC are not well known. These errors feed into the estimate of the precision with which the cross-section can be measured and hence affect the estimate of $V_{\rm tb}$. For this reason one of the goals of this analysis is to find cuts which will eliminate the W+jets and $\rm Wb\overline{b}$ backgrounds, thereby minimizing their effect on the $V_{\rm tb}$ measurement. Once ATLAS begins taking data these backgrounds will be studied in detail as they are common backgrounds to many ATLAS physics searches. The $\rm t\overline{t}$ background at the LHC has been calculated to next-to-leading log [13] and will be well measured at the LHC.

Another possible source of error is due to the modeling of the signal and backgrounds by the Monte Carlo generators. In particular, the only W+jets events which contribute to the background are in the regions of large invariant mass and large transverse momentum in the far reaches of the tails of these distributions. Since these are extremely unusual events it is not clear that the simulation is accurate in this regime. This problem of modeling the tails of high rate backgrounds is common among many ATLAS physics analyses. Also, the signal efficiency in this analysis is less than 2%. Very accurate Monte Carlo modeling of the signal is required to avoid introducing errors at this level.

In the measurements of $V_{\rm tb}$ at ATLAS systematic errors are likely to play a significant role. In particular, since this is a cross-section measurement, the effect of the error in luminosity measurement will need to be studied in detail. If the luminosity is known to better than 7.5%, then the theoretical errors will still dominate. The foreseen uncertainty on the luminosity is estimated at 5-10% [20].

7 Conclusions and Outlook

It has been shown that a significant signal can be seen for s-channel single top production at the LHC after three years at low luminosity. Using top decays to electrons or muons the fractional statistical error on V_{tb} is found to be 2.8%. Without considering systematic errors arising from detector effects, the dominant source of error in the measurement of V_{tb} is the theoretical error on the W^* cross-section.

Since the shape of the W^* signal is similar to its background, it will be necessary to perform independent measurements of the rates of each of the backgrounds at ATLAS to be convinced that a W^* signal has been observed. Since the processes are all of high rate, they will be studied extensively at ATLAS as backgrounds to many physics searches.

Further work to recognize an electroweak top signature could take the form of a polarization analysis. The angular distributions of non-single-top backgrounds are expected to differ substantially from that of the highly polarized top from W^* production. An observed forward-backward asymmetry in the charged lepton angular distribution as measured in the top rest frame would be a indication of the presence of electroweak top production.

Acknowledgements

This work has been performed within the ATLAS collaboration and we thank collaboration members for their helpful discussions. We have made use of the physics analysis framework and tools which are a result of collaboration-wide efforts. We would like to acknowledge the assistance of Raymond Brock and John Parsons who have given suggestions to improve this analysis and this note. We are also grateful to Tim Tait and C.P. Yuan for their help in using the ONETOP package. This work has been supported by the Natural Science and Research Council of Canada.

References

[1] "LHC White Book", CERN/AC/93-03;"LHC Conceptual Design Report, CERN/AC/95-05.

[2] ATLAS Collaboration, "Technical Proposal for a General Purpose pp Experiment at the Large Hadron Collider at CERN", CERN/LHCC/94-43, LHCC/P2, 15 December 1994.

[3] Seltzer, T., Sullivan, Z. and Willenbrock, S., "Single-top-quark Production at Hadron Colliders". hep-ph/9807340, July 1998.

[4] Mahlon, G. and Parke, S., private communication.

[5] Willenbrock, S., “Top Quark Physics for Beautiful and Charming Physicists”. hep-ph/9709355, 15 September 1997.

[6] Particle Data Group, “Review of Particle Physics”. Eur. Phys. J. C 3 1-794 (1998).

[7] Konigsberg, J., “Top and Higgs at the Tevatron: Measurements, Searches, Prospects”, Fermilab-Conf-99/129E, Published Proceeding, 17th International Workshop on Weak Interactions and Neutrinos (WIN 99), cape Town, South Africa, 1999.

[8] Tait, T. and Yuan, C.P., “The Phenomenology of Single Top Quark Production at the Fermilab Tevatron”, hep-ph/9710372, October 1997.

[9] Tait, T., private communication and Huston, J. et al. “Study of the Uncertainty of the Gluon Distribution”, hep-ph/9801444, January 29, 1998.

[10] Willenbrock, S., “Overview of Single Top Theory - Measuring the Cross-section, Theoretical Uncertainties, $|V_{\rm tb}|$, etc.”, Talk presented at the “Thinkshop, Top-Quark Physics for Run II” at Fermi National Laboratory, Bhatavia, Illinois, October 16-18th, 1998.

[11] Smith, M. and Willenbrock, S., “QCD and Yukawa corrections to single top production via $q\overline{q} \rightarrow t\overline{b}$”. Physical Review D, Volume 54, page 6696, 1996.

[12] Stelzer, T., Sullivan, Z., Willenbrock, S., “Single-Top-Quark Production via W-Gluon Fusion at Next-to-Leading Order”. Physical Review D56:5919-5927, 1997.

[13] Bonciani, R., Catani, S., Mangano, M. and Nason, P., “NLL Resumation of the Heavy-Quark Hadroproduction Cross-Section”. Nuclear Physics B. 529:424-450, 1998.

[14] G. Marchesini, B.R. Webber, G. Abbiendi, I.G. Knowles, M.H. Seymour and L. Stanco, “ A Monte Carlo Event Generator for Simulating Hadron Emission Reactions with Interfering Gluons”, Computer Phys. Commun. 67(1992) 465.

[15] Berends, F.A., Kuijf, H., Tausk, B. and Giele,W.T., “On the Production of a W and Jets at Hadron Colliders”, Nucl.Phys.B357:32-64,1991.

[16] D.O. Carlson, “Physics of Single Top Production at Hadron Collider”, Michigan State U. Ph.D. Thesis, UMI-96-05840-mc (microfiche), 1995. 126pp. S. Mrenna, T. Tait, and C.-P. Yuan, private communication.

[17] Sjostrand, T., "High-Energy Physics Event Generation with PYTHIA 5.7 and JET-SET 7.4", Computer Physics Communications 82 (1994) 74.

[18] Richter-Was, E., Froidevaux, D., Poggioli, L., "ATLFAST 2.0 a fast simulation package for ATLAS", ATLAS Internal Note: ATL-PHYS-98-131.

[19] Mangano, M., "Production of W Plus Heavy Quark Pairs in Hadronic Collisions" Nuclear Physics, v.405 page 536 (1993).

[20] "ATLAS Detector and Physics Performance Technical Design Report", Volumes I and II CERN/LHCC/99-14 and CERN/LHCC99-15, May 1999.