PROCEEDINGS OF SCIENCE

$t\bar{t}$ production at ATLAS and $t\bar{t}$ Monte-Carlos

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This talk presents the current experience of the ATLAS collaboration with the available Monte-Carlo generators for $t\bar{t}$ production in the LHC environment.

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1. Introduction

The $t\bar{t}$ production at the LHC is predicted to take place via two distinct hard processes:

- The $gg \to t\bar{t}$ process, which at LHC energies will contribute about 90% to the total production rate, and
- the $q\bar{q} \to t\bar{t}$ process which contributes the remaining 10% to the overall $t\bar{t}$ production cross-section.

The produced top-quark subsequently decay almost exclusively into a W boson and a b-quark and the W bosons then further decay into fermion pairs. Due to a large top quark mass of about 175 GeV the decays occur before any gluon radiation from top-quarks can take place which substantially reduces the complexity of the differential cross-section calculations and modeling of the processes involved. The Feynman diagrams for the two production channels involved in this $2 \to 6$ particle process are shown in Figure 1.

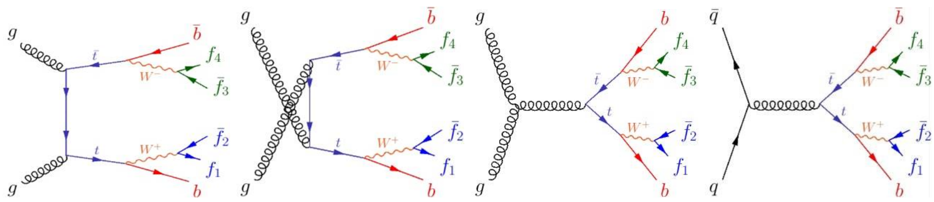

Figure 1: The Feynman diagrams contributing to the $t\bar{t}$ production processes at the LHC.

As one can observe the processes consist of a t-channel $t\bar{t}$ production in case of the colliding gluon and s-channel production in case of the colliding quarks in the initial state. In both cases two sequential resonant (Breit-Wigner type) decays of top-quarks and W bosons take place. An important point to observe is also the fact that there exist observable angular (spin) correlations between the decay products of the two top-quarks.

The cross-section calculations for the $t\bar{t}$ production at LHC have at present already been performed at NNLO level; at ATLAS generally the NLO cross-section for the inclusive $t\bar{t}$ production is taken to be $\sigma(t\bar{t}) = 830 \pm 100$pb, as given by the MC@NLO Monte-Carlo generator [1] and the main sources to the quoted uncertainty are the choice of factorisation/renormalisation scale and the predicted uncertainties in the parton distribution functions (PDF-s). The corresponding leading order (LO) cross-section predictions for the production cross-section differ substantially from the NLO (and NNLO) calculations and are by almost a factor two lower.

2. Overview of the Available Monte-Carlo Tools

As it turns out the Monte-Carlo generation of the $t\bar{t}$ hard process using the full $2 \to 6$ matrix element (ME) calculation and the corresponding 6-body phase space is quite difficult to accomplish. To simplify the event generation procedure simplifications are often used, the most common approach being:

- Generate events using a $2 \to 2$ matrix element and phase-space sampling, i.e. generate on-shell top-quark pairs from hard processes $gg \to t\bar{t}$ and $q\bar{q} \to t\bar{t}$.

- Perform the kinematic smearing of the produced top-quark four-momenta according to the Breit-Wigner shape of the top-quark resonance, using its predicted mass and width as the input parameters.

- Perform subsequent top-quark decays starting from the smeared top-quark momenta, possibly taking into account the polarisation information of the top-quarks obtained in the first step of the procedure.

While this procedure is only approximate it turns not to be too-far off from the exact $2 \to 6$ predictions; the full $2 \to 6$ treatment is of course preferable.

In the last years there has been substantial progress in the development of the Monte-Carlo tools which perform the $t\bar{t}$ hard process generation. The list of tools currently used at ATLAS with its advantages and shortcomings is as follows:

- **Pythia** [2] event generator is the oldest on the 'market'. It uses the $2 \to 2$ approximation described above and the LO matrix element calculation. It does not take into account spin correlations of the top decay products. It is however easy to use and extremely well documented.

- **TopRex** [3] performs the top pair production in a manner very similar to Pythia but includes the re-calculated top-quark polarisation information in the angular (spin) correlations of the decay products. Its strong point is also the possibility of performing 'exotic' (non - Standard Model) top quark decays.

- **Alpgen** [4] also uses the LO $2 \to 2$ calculation and includes polarisation information in the top quark decays; it however does not at present perform any Breit-Wigner smearing of the top-quark and W-boson masses so both of them are kept on-shell with their nominal masses only. Its particular strong point is that the inclusion of extra light jets is possible in the top quark event generation and matrix element calculation, giving accurate predictions for well separated jets (in transverse momentum and cone distance) for $t\bar{t}$ + up to four light jets in the final state.

- **MC@NLO** [1] uses the $2 \to 2$ approximation but performs the matrix element calculation and event generation at next-to-leading (NLO) order in a theoretically consistent manner. The top-quark and W boson masses are smeared but the performed top-quark decays are at present unpolarised, i.e. no spin correlation effects are taken into account.

- **AcerMC** [5] uses the full $2 \to 6$ leading order matrix element calculation and phase space sampling; the Breit-Wigner shapes of the top-quark and W-boson propagators as well as the spin correlations between the decay products are subsequently taken into account implicitly.

As one can observe each of the event generators has its advantages and shortcomings; in order to be aware of the possible differences in the predictions at ATLAS various generators are sistematically compared in the preparatory analysis studies.

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At this point the issue of the $2 \rightarrow 2$ approximation can be examined a bit further, namely one should discuss why the full $2 \rightarrow 6$ event generation is so difficult to achieve. There are two separate issues involved:

- The full $gg(q\bar{q}) \rightarrow t\bar{t} \rightarrow b\bar{b}f_1f_2f_3f_4$ matrix element is very tedious to be calculated by hand. This issue has fortunately been solved by the appearance of automated tools for (LO) matrix element calculations, the Madgraph/HELAS [6] package being on the forefront of them.
- Efficient phase space sampling for a 6-body final state is very difficult to achieve. One has to stress that experimentalists want **unweighted events** to be produced by Monte-Carlo tools which can subsequently be passed through the complex detector simulation/digitization/ reconstruction chain. The complexity of the phase-space sampling increases with the number of Feynman diagrams contributing to the process cross-section and with the number of particles in the final state. Also difficult to describe accurately are the invariant mass distributions of heavy particles produces at their kinematic thresholds.

From this perspective it seems worth discussing the newest Monte-Carlo event generator used at ATLAS, namely the AcerMC Monte-Carlo generator, in more detail.

2.1 AcerMC Monte-Carlo Generator

AcerMC Monte-Carlo Generator (the present version being 2.4) is a Monte Carlo generator for a select list of processes at the ATLAS/LHC environment. The list of implemented processes includes the full $2 \rightarrow 6$ top quark pair production involving the four Feynman diagrams given in Figure 1 as well as the production of $gg(q\bar{q}) \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}f_1f_2f_3f_4$ including the non-resonant Feynman diagrams (i.e. not involving top quark intermediate states) which number 45 in total. The non-resonant contributions contribute only a few percent to the total top-quark pair production cross-section (see Table 1) but give a substantial impact when the $t\bar{t}$ production is considered as a background process in the Higgs searches at the LHC [7]. Detailed studies also show that the full $2 \rightarrow 6$ treatment might have a slight impact on the decay product polarisation studies compared to the event generators using approximate $2 \rightarrow 2$ event generation [8].

Process	$\sigma\,(Q^2 = (2 \cdot m_t)^2) [pb]$
$gg \rightarrow t\bar{t} \rightarrow b\bar{b}\mu^+\bar{\nu}_\mu\mu^-\nu_\mu$	4.49
$q\bar{q} \rightarrow t\bar{t} \rightarrow b\bar{b}\mu^+\bar{\nu}_\mu\mu^-\nu_\mu$	0.75
$gg \rightarrow b\bar{b}\mu^+\bar{\nu}_\mu\mu^-\nu_\mu$	4.77
$q\bar{q} \rightarrow b\bar{b}\mu^+\bar{\nu}_\mu\mu^-\nu_\mu$	0.77

Table 1: AcerMC predictions for the total cross-section for $2 \rightarrow 6$ processes involving only resonant ($t\bar{t}$) and resonant and non-resonant final final states at the LHC

The matrix elements used in AcerMC are produced by the Madgraph/HELAS tool. The emphasis of the AcerMC development is given to the development of Monte-Carlo algorithms for efficient phase-space sampling and production of unweighted events. The phase space sampling is thus done by using a sequence of advanced approaches implementing importance sampling techniques:

- Adaptive multi-channel approach [9].
- Revised Kajantie-Byckling phase space factorisation [10, 11].
- AcerMC native 'massive' importance sampling functions [11].
- Additional adaptive algorithm based on the modified VEGAS approach [12].

Using this approach the unweighting efficiency for top quark pair production is on the order of 15% which is deemed to be a very good result compared to the other available Monte-Carlo tools.

3. Showering/Fragmentation Generators used at ATLAS

At ATLAS two primary generators are used for showering and fragmentation of the hard processes produced by various generators mentioned in the previous Sections.

- **HERWIG 6.507.2** [13] incorporating some discovered bug-fixes not yet included in the official release; in addition Jimmy [14] algorithm is used for the underlying event simulation.
- **Pythia 6.324** [2] with a new showering and underlying event modeling.

A substantial effort is being made in preparing the tunings for the two generators. Substantial progress has been made in developing the tuning tools to propagate the measurements of the underlying event properties at Tevatron to the predictions about the underlying event properties at the LHC. In addition, tools for tuning the initial and final state radiation as well as the fragmentation parameters of the two generators on first LHC data are in preparation within the working groups of the ATLAS collaboration.

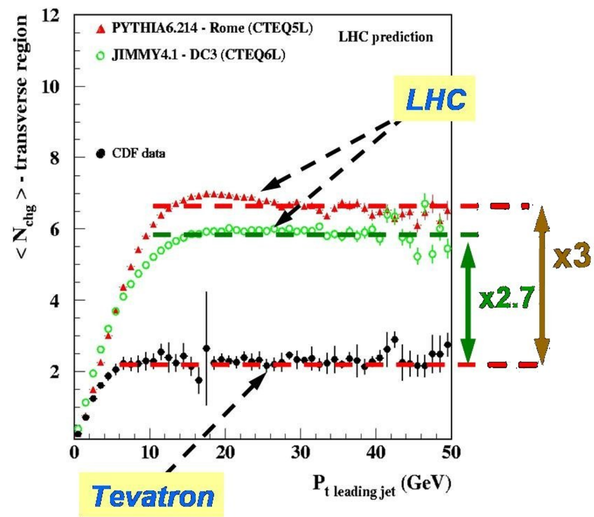

Figure 2: Comparison of underlying event predictions of the charge multiplicity as a function of the transverse momentum of the leading jet in the event for different underlying event models using ATLAS tunings based on Tevatron and UA5 data.

Work done by A. Moraes *et.al* (at present unpublished) is an excellent example of the tuning of the underlying event predictions for the $t\bar{t}$ events at the LHC using Tevatron and UA5 data. As one can observe in Figures 2 and 3 the different underlying event models give predictions which have observable differences but nevertheless seem not to be too far apart.

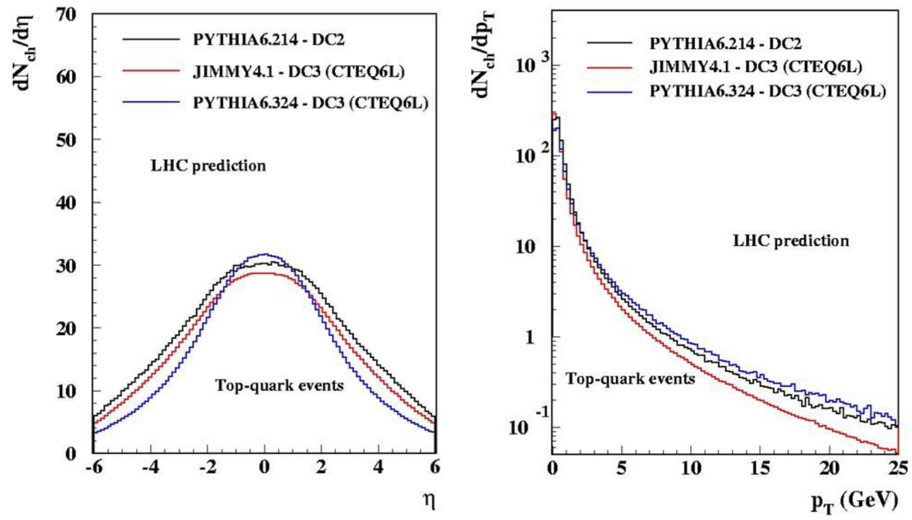

Figure 3: Comparison of underlying event predictions for different underlying event models using ATLAS tunings based on Tevatron and UA5 data.

4. Conclusions

At ATLAS a wide variety of different Monte-Carlo generators for $t\bar{t}$ production is used. Each of the generators has been demonstrated to have its strong (and weak) points, however to have a hold on the possible systematics differences it is advantageous to use as many of them as possible. At ATLAS we also believe to have an edge by using the AcerMC Monte-Carlo generator of full $2 \to 6$ production processes with resonant and non-resonant contributions. We also use different showering and fragmentation tools as well as different underlying event models with promising tuning procedures being implemented. To sum up: A lot of work is still to be done but we strongly believe we will be well prepared for the first top events next year!

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