Towards a Monte Carlo Event Generator for $t\bar{t}$ production at threshold

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One of the most important physics targets for the ILC will be the precision measurements of the top quark properties, and especially the top quark mass. Top-antitop production at threshold provides the ideal environment for making such measurements but is complicated by the machine's luminosity spectrum and thus needs to be carefully studied to understand the constraints involved and the potential precision reach. We present recent developments in the tools needed to make such studies, and in particular, progress towards a NNLO $t\bar{t}$ event generator at threshold with luminosity spectrum effects included.

1 Introduction

The measurement of top quark properties (mass, width, couplings) are some of the guaranteed highlights of the ILC physics program. The most promising method for these measurements is performing an energy scan around the $t\bar{t}$ production threshold ($\sqrt{s} \approx 350GeV$). From the location and rise of the cross section lineshape, information about the top quark mass can be obtained, while from the shape and normalization one can extract information about the top quark width (Γ_t), the strong coupling constant (α_s) and the top-Yukawa coupling (y_t).

The main complication with such a measurement comes from the machine's luminosity spectrum. At the ILC, the distribution of luminosity as a function of real collision energy $d\mathcal{L}/dE$, called the luminosity spectrum, is a consequence of various energy loss mechanisms such as initial state radiation, beamstrahlung and machine energy spread. How the three components contribute to the luminosity spectrum can be seen in figure 1.

The luminosity spectrum directly affects the experimental cross section by the relation :

$$\sigma_{t\bar{t}}^{obs}(\sqrt{s}) = \int_0^1 dx_1 dx_2\, \mathcal{L}(x_1, x_2, \sqrt{s}) \times \sigma_{t\bar{t}}^{th}(x_1, x_2, \sqrt{s}) \tag{1}$$

where $\sigma_{t\bar{t}^{obs}}$ is the experimental cross section, $\sigma_{t\bar{t}^{th}}$ is the theoretical cross section, $\mathcal{L}$ is the machine's luminosity spectrum and $x = \sqrt{s}/\sqrt{s_0}$ the scaled centre of mass energy.

The effect this has on the $t\bar{t}$ cross section can be seen in figure 1 where the three components of the luminosity spectrum have been simulated and applied to the theoretical cross section. The resonant-like structure that is present in the theoretical cross section curve flattens out in the observed one.

In order to make high precision top quark measurements using a threshold scan at the ILC, it is very important to have a precise understanding of both the theoretical quantities and the luminosity spectrum of the machine.

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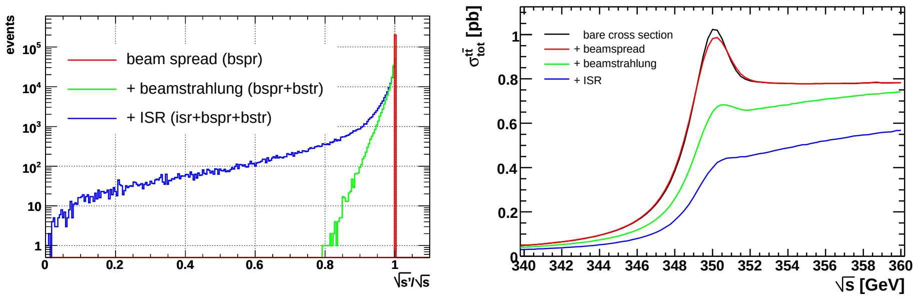

Figure 1: Left - The three components of the luminosity spectrum. Right - Smearing the $t\bar{t}$ cross section with the different components of the luminosity spectrum.

2 Threshold Simulations

In the past, a lot of effort has gone towards the understanding of the theoretical aspects [2, 3, 4, 5] of the top quark threshold at the ILC. On the experimental side, there have been studies [6, 7, 8] examining the impact of the luminosity spectrum on such a measurement. However, these studies were done in a naive way by smearing the theoretical cross section (using Eqn. 1) with a simulated luminosity spectrum or by moving on to a simpler form for the top threshold [9].

So far no studies have been done at the event by event level, examining the effect the luminosity spectrum could have on a detailed simulation of the measurement. The reason for this is that so far no event generator existed that could precisely describe the $t\bar{t}$ threshold. This is manifested in figure 2, where the cross section prediction for the threshold region from general purpose event generators (in this case Pandora [10] and Herwig [11]) are compared with a high precision (NNLO in QCD) calculation [3].

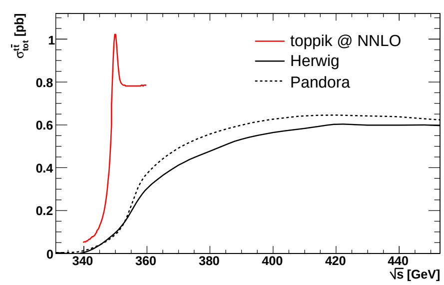

Figure 2: Comparison of $t\bar{t}$ cross section predictions from Pandora, Herwig and NNLO QCD calculation by TOPPIK [3].

A further argument for going to fully differential event generator based simulations of the $t\bar{t}$ threshold is that for top quark studies, except from the total cross section, information also exist in the top quark momentum distributions [12] by using the forward-backward assymetry A_{FB} and the location of the peak in the top momentum distribution P_{peak}[6]. The top momentum distributions are sensitive to the top quark mass M_t and strong coupling constant α_s, but not on the top quark width Γ_t thus having different correlations of these three quantities than the cross section (which does depend on Γ_t). So they can provide another useful observable for disentangling the measured quantities and reducing the errors on the measurement. Also, the integral of Eqn. 1 does not include relativistic boost effects which will modify the experimental distributions and hence the sensitivity to observables such as A_{FB} and P_{peak}.

Furthermore, the process $e^+e^- \to t\bar{t}$ also contains information about the electroweak sector through the sensitivity to the γ and Z couplings [12]. This would manifest itself in the angular distribution of the top quarks which would also require a fully differential study of the process. It is therefore fundamental for the $t\bar{t}$ threshold that a fully differential event generator based study that includes the effects of the luminosity spectrum is performed.

3 $t\bar{t}$ threshold event generator

The QCD NNLO code TOPPIK [3] was choosen as the calculation program of the generator due to its high order calculation, the simplicity and availability of the Fortran code and the availability of corrections (NNLL for total cross section [4], NLO for rescattering corrections [5]). TOPPIK performs a fully differential calculation by solving the Lippmann-Schwinger equation in momentum space resulting in two sets of Green functions, one for the S-wave and one for the P-wave contributions accounting for the vector and axial-vector current contributions to the process, which encode all the information about the $t\bar{t}$ system.

The problem with using TOPPIK as an event generator is that it is too slow[a] in calculating the quantities required by Eqn. 1 for any one phase space point $(\sqrt{s}, M_t, \Gamma_t, \alpha_s, M_H)$. This makes it impossible to use in applications such as the variable energy system of Eqn. 1 as speed is essential both for large scale event generation and for fitting.

This problem is solved by the use of a multidimensional interpolation technique. By precalculating and storing a look up table of Green functions over the required phase space (i.e. $\sqrt{s}, M_t, \Gamma_t, \alpha_s$) and performing interpolations on these quantities for every future call to TOPPIK, a relative speed-up of $\times 5$ for interpolations in all parameters, and $\times 10^6$ for interpolations in only $\sqrt{s}$ is achieved.

For the generation procedure, the monte carlo integration is done using the general purpose adaptive simulator FOAM [15] by integrating over all phase space variables and weighting the generation by the integral of Eqn. 1.

This should result into events being produced according to the correct weight of the luminosity spectrum folded cross section. The top plot of figure 3 shows the average weight for 10^4 events at each point in $\sqrt{s}$ compared to the theoretical and experimental cross sections (beamstrahlung only). There is reasonable agreement between the smeared cross section and the generator based events upto the peak of the curve. The reason for disagreement beyond the peak is that FOAM is not optimized for integrating highly peaked distributions such as the luminosity spectrum. This problem has been encountered in the past and a

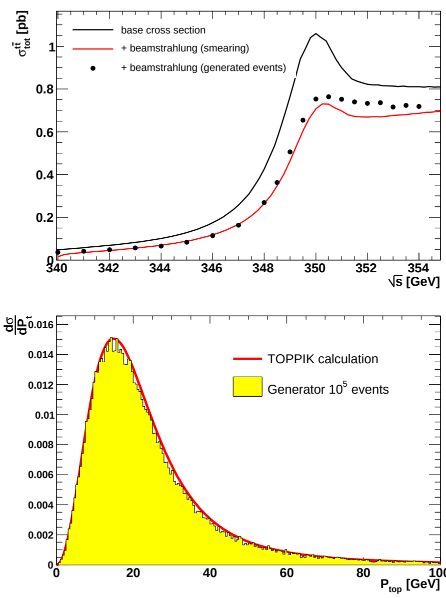

Figure 3: Top - Cross section with beamstrahlung using smearing and generator. Bottom - t Comparison of momentum distribution (no energy loss).

[a]More than 1.5sec per event calculation.

solution is possible by optimizing FOAM [15].

The generator produces $t\bar{t}$ pairs which are boosted according to any assymetry in beam energy and then decayed to b quarks and W's following a 2-body decay. The top momentum distribution for 10^5 generated events can be seen in the bottom plot of figure 3. There is good agreement between the calculated and generator based momentum distributions. This comparison was done by considering only the S-wave part of the process. Inclusion of the P-wave contribution and interference terms is trivial.

The resulting bW pairs will be given to a general purpose hadronization package (e.g. Pythia [14]) for further decays and hadronization. The interface of the NNLO calculation to QCD parton shower models should be simple because due to the large width of the top quark, its lifetime is very small thus suppressing QCD radiation which would complicate the interface of the different order calculations (double-counting etc.).

4 Summary

The effort towards a $t\bar{t}$ threshold event generator with luminosity spectrum effects included was presented. This is important both for a detailed study of the precision reach of the ILC at the $t\bar{t}$ threshold, but also to understand the effect of the luminosity spectrum on the event by event basis and the requirements on the luminosity spectrum and beam energy measurements for precision threshold physics ($t\bar{t}$, W^+W^-, SUSY thresholds etc.) at the ILC.

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