Applying the POWHEG method to top-pair production and decay at the ILC

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Outline

1. An introduction to the POWHEG NLO method
2. Applications of the POWHEG method
3. Top-pair production and decay at the ILC (arXiv:0806.4560)
4. Plots
5. Summary

An introduction to the `POWHEG` NLO method

Parton shower (PS) vs. Matrix Element (ME) Generators

- An ME generator calculates the exact N$^{(>0)}$LO cross-section and distributes events according to the matrix element with partons in the final state e.g. `HELAC`, `Madgraph` whilst,
- a PS generator, starting from an LO configuration, simulates enhanced QCD radiations from the LO partons to all orders with the use of the Sudakov form factor and implements a hadronization model for the final states e.g. `Herwig++, Pythia`.
- With this information, we can draw up the following table illustrating the merits (M) and drawbacks (D) of both generators:

PS generators	ME generators
Resums leading logarithmic contributions to all orders (M)	Can only go up to $\mathrm{N}^{\sim 6}$ LO (D)
Hence, high multiplicity hadrons in the final state (M)	and low multiplicity partonic final states (D)
Works well in regions of low relative p_T (M & D)	Works well in regions of high relative p_T (M & D)
Total rate is accurate to LO (D)	Total rate is accurate to $\mathrm{N}^{(>0)}$LO (M)

Aside: Most PS generators attempt to include NLO corrections via a method called the Matrix Element correction which

- corrects the hardest shower emission *so far* to the exact matrix element and populates the high p_T regions according to the NLO cross-section.

However, the total rate is still only accurate to LO and virtual corrections are not fully taken care of.

Getting the best of both worlds at NLO

Two state-of-the art methods solve this problem:

- The earlier and more familiar Monte Carlo at NLO (MC@NLO) method (hep-ph/0204244) and the
- relatively new Positive Weighted Hardest Emission Generation (POWHEG) method (hep-ph/0409146).

Both methods

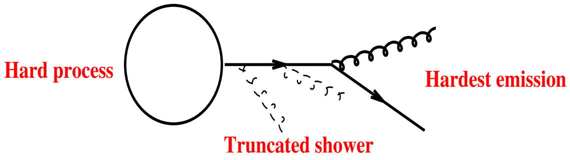
- have total rates accurate to NLO,
- treat hard emissions as in ME generators,
- treat soft and collinear emissions as in PS generators,
- and generate a set of fully exclusive events which can be interfaced with a hadronization model.

In this talk, we will focus on the description and applications of the `POWHEG` method in conjunction with the PS generator, `Herwig++`.

Positive Weighted Hardest Emission Generation

The attributes of the POWHEG method are as follows:

- It generates the hardest emission in the shower first to NLO accuracy using a modified Sudakov form factor.
- For angular ordered showers like Herwig++, it includes a truncated shower of soft, wide angled emissions from the hard scale to the scale of the hardest emission. This maintains the correct soft emission pattern.



- It then showers the resulting partons subject to a p_{T} veto to ensure that no harder emissions are generated.
- Unlike MC@NLO, it is independent of the PS generator used.
- Unlike MC@NLO, all events have positive weight.

The parton shower hardest emission cross-section

- For a single parton, the cross-section for the hardest emission with transverse momentum $p_{\rm T}$ is given by,

$$d\sigma = d\sigma_{\rm B}\left[\Delta_{\rm V}(0) + \Delta_{\rm V}(p_{\rm T})\frac{\alpha_{\rm S}}{2\pi}Pdz\frac{dq^2}{q^2}\right], \qquad (1)$$

where P is the splitting function for the hardest emission and $\Delta_{\rm V}(p_{\rm T})$ is the Sudakov form factor for no emissions with $k_{\rm T} > p_{\rm T}$ which is given by

- $$\Delta_{\rm V}(p_{\rm T}) = \exp\left[-\int dz\frac{dq^2}{q^2}\frac{\alpha_{\rm S}}{2\pi}P\Theta(k_{\rm T}-p_{\rm T})\right] \qquad (2)$$

- The cross-section (1) expanded to order $\alpha_{\rm S}$ gives

$$d\sigma = d\sigma_{\rm B}\left[\left\{1-\int\frac{\alpha_{\rm S}}{2\pi}Pdz\frac{dq^2}{q^2}\right\} + \frac{\alpha_{\rm S}}{2\pi}Pdz\frac{dq^2}{q^2}\right]. \qquad (3)$$

- The POWHEG method aims to substitute (3) with the exact NLO result within the parton shower.

Correcting to the exact NLO cross-section

- The exact NLO cross-section can be written as

$$d\sigma_{\mathrm{NLO}} = d\sigma_{\mathrm{B}} + d\sigma_{\mathrm{V}} + d\sigma_{\mathrm{R}} \equiv d\sigma_{\mathrm{B}} + d\sigma_{\mathrm{V}} + d\sigma_{\mathrm{B}} dr\,\mathcal{M}\,. \quad (4)$$

- Adding and subtracting $d\sigma_{\mathrm{B}} \int_\delta dr(\mathcal{M} - \mathcal{C})$ we get

$$\begin{aligned} d\sigma_{\mathrm{NLO}} &= d\sigma_{\mathrm{B}} + d\sigma_{\mathrm{V}} + d\sigma_{\mathrm{B}} \int_\delta dr(\mathcal{M} - \mathcal{C}) \\ &+ d\sigma_{\mathrm{B}} dr\,\mathcal{M} - d\sigma_{\mathrm{B}} \int_\delta dr(\mathcal{M} - \mathcal{C})\,. \end{aligned} \quad (5)$$

where $\mathcal{C}$ is a counter-term and δ is the subtraction region.

- This can be rearranged to give

$$\begin{aligned} d\sigma_{\mathrm{NLO}} &= d\sigma_{\mathrm{V'}} + d\sigma_{\mathrm{B}} \int_\delta dr(\mathcal{M} - \mathcal{C}) \\ &+ d\sigma_{\mathrm{B}} \left[\left\{ 1 - \int_\delta dr\,\mathcal{M} \right\} + \mathcal{M} dr \right] \end{aligned} \quad (6)$$

with $d\sigma_{\mathrm{V'}} = d\sigma_{\mathrm{V}} + d\sigma_{\mathrm{B}} \int_\delta dr\,\mathcal{C}$ now finite.

Correcting to the exact NLO cross-section

- Comparing (6) with (3) below,

$$d\sigma = d\sigma_{\mathrm{B}}\left[\left\{1 - \int \frac{\alpha_{\mathrm{S}}}{2\pi} P dz \frac{dq^2}{q^2}\right\} + \frac{\alpha_{\mathrm{S}}}{2\pi} P dz \frac{dq^2}{q^2}\right] ,$$

- we can write down an analog of (1) below

$$d\sigma = d\sigma_{\mathrm{B}}\left[\Delta_{\mathrm{V}}(0) + \Delta_{\mathrm{V}}(p_{\mathrm{T}}) \frac{\alpha_{\mathrm{S}}}{2\pi} P dz \frac{dq^2}{q^2}\right]$$

as

$$d\sigma_{\mathrm{NLO}} = d\sigma_{\bar{\mathrm{B}}}\left[\Delta_{\mathrm{NLO}}(0) + \Delta_{\mathrm{NLO}}(p_{\mathrm{T}}) \mathcal{M} dr\right] \tag{7}$$

where

$$d\sigma_{\bar{\mathrm{B}}} = d\sigma_{\mathrm{B}} + d\sigma_{\mathrm{V}'} + d\sigma_{\mathrm{B}} \int_{\delta} dr (\mathcal{M} - \mathcal{C}) *$$

$$\Delta_{\mathrm{NLO}}(p_{\mathrm{T}}) = \exp\left[- \int \mathcal{M} \Theta(k_{\mathrm{T}} - p_{\mathrm{T}})\right] . \tag{8}$$

*Note that in defining $d\sigma_{\bar{\mathrm{B}}}$, we have neglected terms of higher order than α_{S} and if negative, P.T. has broken down.

POWHEG formalism

- With

$$d\sigma_{\mathrm{NLO}} = d\sigma_{\bar{\mathrm{B}}}\left[\Delta_{\mathrm{NLO}}(0) + \Delta_{\mathrm{NLO}}(p_{\mathrm{T}})\mathcal{M}dr\right] , \qquad (9)$$

the POWHEG method can be applied by

- generating the p_{T} of the hardest emission and its emission variables r, according to the term in [...], using well known Monte Carlo techniques,
- distributing the underlying Born variables according to $d\sigma_{\bar{\mathrm{B}}}$, (This defines the event weight and since it is always positive definite, all event weights are positive)
- for angular ordered showers, implementing a truncated shower of soft emissions between the *hard* scale and the scale of the hardest emission,
- and finally showering the resulting partons as in a PS generator subject to a p_{T} veto.

Applications of the POWHEG method

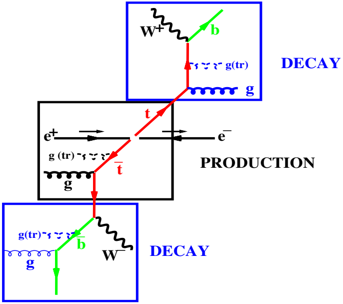
The POWHEG method has been applied successfully to the following processes

- Z **pair hadroproduction**: Nason and Ridolfi: hep-ph/0606275
- **Heavy flavour production**: Frixione, Nason and Ridolfi: arXiv:0707.3088
- e^+e^- **annihilation to hadrons**: L-D, Gieseke and Webber: hep-ph/0612281
- **Drell-Yan vector boson production**: Alioli, Nason, Oleari and Re: arXiv:0805.4802; Hamilton, Richardson and Tully:arXiv:0806.0290

A truncated shower of at most one extra gluon emission was implemented for the e^+e^- annihilation process and a full shower was implemented for Drell-Yan production by the latter collaboration.

Both truncated showers were found to give only a slight improvement to the data fits.

Top-pair production and decay at the ILC



- Spin correlations due to polarized incoming leptons are taken into account in the matrix elements, $\mathcal{M}$ for the production and decays of the top pairs.
- The narrow width approximation is applied so that production and decay interference can be neglected.
- This independence enables us to apply the method in separate frames: the lab frame for production and the top rest frame for its decay.

Top-pair production and decay at the ILC

- In the lab frame, the transverse momentum k_T is defined relative to the original $t - \bar{t}$ axis whilst in the top rest frame it is relative to the original $b - W$ axis.
- The scale range available for production emissions ($\approx \log(\sqrt{s}/m_{\mathrm{t}})$) and is much less than the range available for decay emissions ($\approx \log(m_{\mathrm{t}}/m_{\mathrm{b}})$).
- There are two different sources of the decay emissions: one from the top quark before it decays and the other from the *b* quark after the decay.
- Hence, there are three different regions for truncated emissions:
  - Before the hardest emission in the production,
  - From the top quark before it decays,
  - Before the hardest emission from the *b* quark.

Top-pair production and decay at the ILC

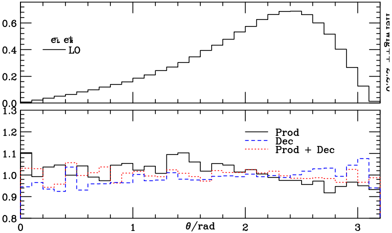
Setting $\sqrt{s} = 500$ GeV and $m_t = 175$ GeV, we considered the following four cases with `POWHEG` interfaced with `Herwig++`:

- Leading order (LO) with no `POWHEG` emissions,
- Only `POWHEG` emissions in the production process, (Prod),
- Only `POWHEG` emissions in the decays of the tops, (Dec),
- Both production and decay emissions allowed, (Prod + Dec).

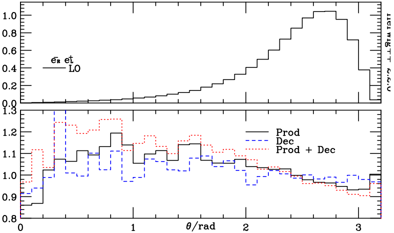
For the two different e^+e^- initial polarizations, we investigated the correlations between the decay products (we consider leptonic decays only for the W bosons) and the momentum distributions of the b quarks before hadronization.

Plots

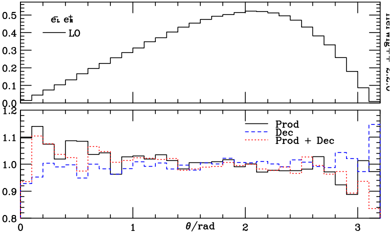
Angle btw decay e^- and t (LR).



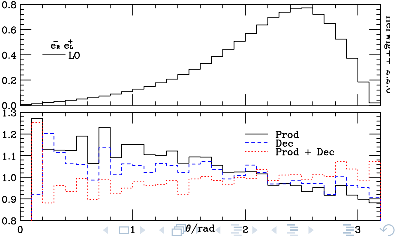
Angle btw decay e^- and t (RL).



Angle btw decay e^+ and e^- (LR).

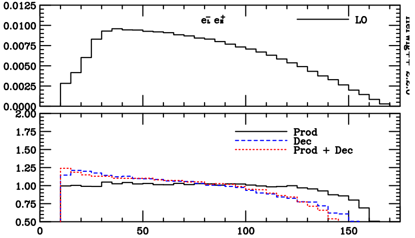


Angle btw decay e^+ and e^- (RL).

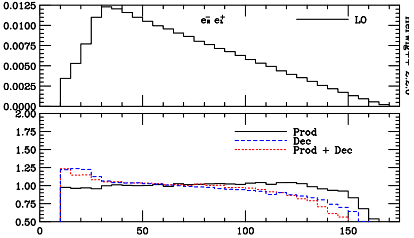


Plots

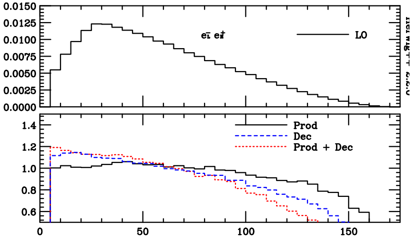
Energy of b quark in lab frame (LR)



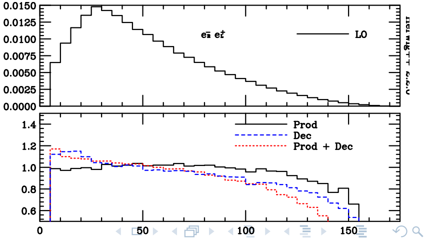
Energy of b quark in lab frame (RL)



p_{T} of b quark in lab frame (LR)

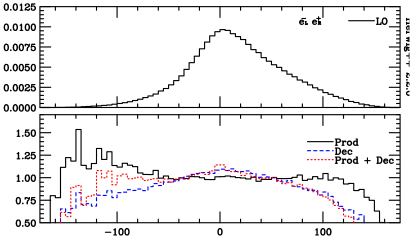


p_{T} of b quark in lab frame (RL)

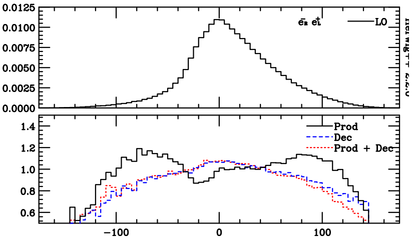


Plots

Longitudinal momentum of *b* quark in lab frame (LR)



Longitudinal momentum of *b* quark in lab frame (RL)



Summary

- NLO improvements of parton showers are essential for near accurate predictions of angular correlations and momentum distributions at future colliders.
- The POWHEG method achieves this by distributing the *hardest* emission according to the NLO matrix element and yields events with positive weights. For angular ordered showers, the addition of a truncated shower is required.
- The method, though not very straightforward to apply, has demonstrated success in comparison with existing collider data.
- In this talk, we have, with confidence, extended this to top-pair production and decay at the ILC and made predictions for some distributions in comparison to leading order predictions.