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New theoretical results for tW and tH production

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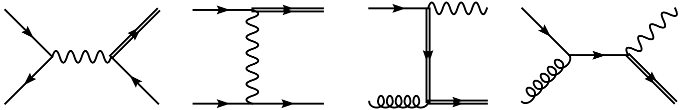
TOP2010, Brugge

Overview

- Brief review of Wt production.
- Interference with $t\bar{t}$ - previous solutions.
- Implementation in MC@NLO.
- Similar methods for Ht production.
- Example physics results.

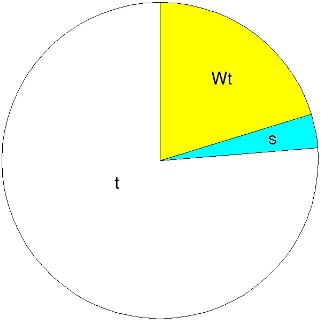
Single top production modes



(1) (2) (3)

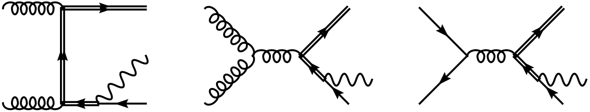
- Three modes of single top production at LO - *s* channel; *t* channel; *Wt* channel.

- Total LHC cross-section (at LO) $\sim$ 320pb (c.f. $\sigma_{t\bar{t}} \sim$ 830pb).
- *s*- and *t*-channel modes well understood theoretically; *Wt* less so.



Interference Problem

- At NLO, have virtual and real corrections to the LO Wt graphs.
- NLO real emission contributions to Wt production include:



- These graphs also contribute to $t\bar{t}$ production (at LO), with decay of the $\bar{t}$.
- Give a large contribution when $m_{bW} \to m_t$.
- Thus at LO have well-defined $\sigma_{t\bar{t}}$ and σ_{Wt}, with $\sigma_{Wt} < \sigma_{t\bar{t}}$.
- At NLO, σ_{Wt} gets a huge correction! Due to contamination from $t\bar{t}$.

Interference problem

- At this point, there are two viewpoints on how to proceed.

Combined Approach

- Only consider $WWb\bar{b}$ states. Meaning of Wt production is lost.
- Calculation valid throughout entire phase space / for generic selection cuts.
- NLO corrections to $t\bar{t}$ cannot be included.
- Low efficiency for Wt-like event generation.

Separated Approach

- Consider Wt and $t\bar{t}$ as separate processes *subject to suitable analysis cuts*.
- Not valid over all phase space.
- Can include NLO corrections to both Wt and $t\bar{t}$ production.
- Can efficiently generate Wt-like events.

Which approach?

- Approximating Wt and $t\bar{t}$ as separate processes remains a subtle, delicate and controversial subject.
- Proponents believe that NLO corrections are more important than interference with resonant top pair production, for certain selection cuts.
- Opponents feel that only a description valid throughout all of phase space, with all interference effects included, makes sense.
- All previous calculations of Wt production beyond LO have necessarily defined separation criteria.
- Let's look at each in turn...

BBD Approach

- Analysis of Wt production given by Belyaev, Boos & Dudko.
- Although not full NLO (no loop diagrams), the interference problem still occurs.
- Wt mode isolated by restricting invariant mass of $W\bar{b}$ pair:

$$|m_{bW} - m_t| > \eta\Gamma_t.$$

- Reduces contribution from phase space region corresponding to $\bar{t}$ resonance.
- Thus reduces $t\bar{t}$ type contributions as required.
- However, this is not an experimental definition - cannot identify W and b from $\bar{t}$.

Tait Approach

- Tait also calculates real emission contributions to Wt.
- Naïve cross-section modified by subtraction term:

$$\sigma_{subt.} = \sigma_{t\bar{t}} \times BR(\bar{t} \to Wb),$$

  i.e. resonant contribution removed explicitly.
- This was compared with the BBD (invariant mass cut) approach.
- Similar total cross-section for:

$$|m_{bW} - m_t| \gtrsim 15\Gamma_t.$$

MCFM Approach

- Fully differential definition of Wt mode given, rather than just for total cross-section (Campbell & Tramontano).
- Relies on a number of different ideas...
- First, a veto is introduced on the transverse momentum of the b quark not coming from the t (no veto if not present).
- Factorisation scale set to $\mu_F = p_t^{(veto)}$.
- $q\bar{q}$ initial states removed.
- Works well at purely NLO level.

MC@NLO Approach

- The previous definitions of Wt work well at NLO, but cannot be immediately extended to a parton shower context.
- A definition of Wt for use in MC@NLO must be:
  1. Applicable when initial and final state radiation are present.
  2. Gauge invariant.
  3. Free of ambiguities outside the doubly resonant region.
- It is also helpful to have a means of checking the approximation i.e. estimating the size of interference effects.
- MC@NLO proceeds by modifying the Wt cross-section with a gauge-invariant local subtraction term:

$$d\sigma_{ab\to Wt} = d\sigma_{ab} - d\sigma_{ab}^{subt}.$$

Subtraction term

- The subtraction term must satisfy the following requirements:
  1. Gauge invariance.
  2. Equal to the top pair contribution when $m_{bW} = m_t$.
  3. Falling off quickly for $|m_{bW} - m_t| > 0$.
- Naïvely, one can write:

$$\sigma_{ab}^{subt} = |\mathcal{A}(ab \to t\bar{t})|^2 \times f_{BW}(M_{\bar{b}W}) \times |\mathcal{A}(\bar{t} \to W\bar{b})|^2,$$

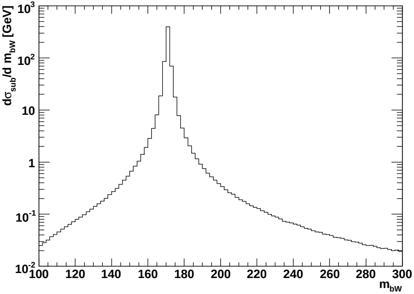
where f_{BW} is the Breit-Wigner function. However:

  1. Kinematics on the LHS is from $ab \to tWb$, but need $\bar{t}$ on-shell on the RHS.
  2. Spin correlations of the top decay products are not included - needed for local matching of matrix elements.

Subtraction term

- Instead use:

$$\sigma_{ab}^{subt} = \underbrace{\left|\tilde{\mathcal{A}}(ab \to tW\bar{b})_{t\bar{t}}\right|^2}_{\text{Reshuffled kinematics} \to \bar{t} \text{ on-shell}} \times \overbrace{\frac{f_{BW}(M_{\bar{b}W})}{f_{BW}(m_t)}}^{\text{Damp if } M_{\bar{b}W} \text{ far from top mass.}} .$$



- Indeed has desired behaviour.

Implementation in MC@NLO

- The above prescription for the *Wt* mode is implemented in MC@NLO v3.4.
- Called *Diagram Subtraction* in the code.
- Also provided is a calculation with doubly resonant diagrams removed at the amplitude level (called *Diagram Removal*).
- The difference between DS and DR measures the size of interference between *Wt* and top pair production.
- Caution: DR not gauge-invariant. Detailed discussion in arXiv:0805.3067.
- Take-home message:

For a given choice of selection cuts, MC@NLO can only be used if DR and DS give similar results. If unsure, *run both codes*.

Example results

- There are two contexts in which one must evaluate $Wt+t\bar{t}$:
    1. Wt is a signal, and $t\bar{t}$ a (significant) background.
    2. Wt and $t\bar{t}$ are backgrounds to a third process (e.g. $H \to WW$).
- It is important to check in both cases that the approximation of separate Wt and $t\bar{t}$ processes indeed seems justified.
- Then NLO corrections can be included in both, thus providing a more accurate description.
- This was examined in detail in arXiv:0908.0631, for the examples of Wt and $H \to WW$ signal cuts...

Wt signal cuts

- We use the following basic cuts:
  1. Exactly one b jet ($p_T > 50$ GeV, $|\eta| < 2.5$). No other b jets with $p_T > 25$ GeV and $|\eta| < 2.5$.
  2. Exactly two light jets with $p_T > 25 GeV$ and $|\eta| < 2.5$. Also, 55 GeV $< m_{j_1 j_2} <$ 85 GeV.
  3. Exactly one isolated lepton ($\Delta R < 0.4$ w.r.t. jets) with $p_T > 25$ GeV and $|\eta| < 2.5$.
  4. Missing transverse energy $E_T^{miss} > 25$ GeV.
- Cuts are fairly minimal - results can only get better with more realistic analysis.
- Also, use a selection of b tagging efficiencies and light jet rejection rates.

Wt as a Signal - Results

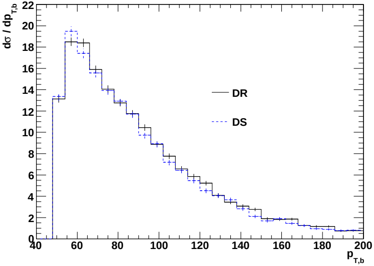
- Have evaluated DR and DS cross-sections for a variety of choices of b-tagging efficiency (e_b) and light jet rejection rate (r_{lj}):

e_b	r_{lj}	σ_{Wt}^{DR}/pb	σ_{Wt}^{DS}/pb	$\sigma_{t\bar{t}}$/pb
1.0	10^4	$1.206^{+0.039}_{-0.017}$	$1.189^{+0.021}_{-0.010}$	$5.61^{+0.74}_{-0.54}$
0.6	30	$0.717^{+0.020}_{-0.014}$	$0.696^{+0.020}_{-0.005}$	$4.29^{+0.45}_{-0.46}$
0.6	200	$0.748^{+0.014}_{-0.011}$	$0.726^{+0.014}_{-0.007}$	$4.36^{+0.56}_{-0.42}$
0.4	300	$0.505^{+0.026}_{-0.009}$	$0.494^{+0.008}_{-0.008}$	$3.31^{+0.40}_{-0.37}$
0.4	2000	$0.512^{+0.011}_{-0.010}$	$0.503^{+0.001}_{-0.007}$	$3.35^{+0.37}_{-0.38}$

- DR and DS agree within scale variation uncertainty.
- Wt production cross-section larger than the scale variation uncertainty of $t\bar{t}$ production.

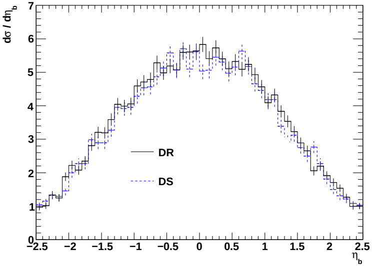
$\Rightarrow$ Wt is indeed a well-defined signal!

Wt as a Signal - Results



- Here we show the transverse momentum and pseudo-rapidity of the *b* jet passing the cuts.

- Confirms that interference is small locally in phase space.



Higgs signal cuts - results

- We also looked at $H \to WW$ cuts Anastasiou, Dissertori & Stöckli.

Process	σ_{NLO}/fb
$H \to WW$	81.8 $\pm$0.4
$t\bar{t}$	12.25 $\pm$ 0.3
Wt (DR)	6.91 $\pm$ 0.06
Wt (DS)	6.89 $\pm$ 0.07

- DR and DS results are identical within statistical uncertainties.
- Wt and $t\bar{t}$ production backgrounds are comparable in size, and a significant fraction of the signal.
- Distributions from DR and DS also agree well (see paper)...

Discussion

- Have shown that for Wt and $H \rightarrow WW$ signal cuts, the approximation of separate Wt and $t\bar{t}$ processes appears to be justified.
- Thus allowing inclusion of NLO (+ parton shower) effects in both.
- Also pointed out in arXiv:0908.0631 that K-factors are different for Wt, $t\bar{t}$ and $H \rightarrow WW$ production.
- Also seen by previous NLO Wt calculations...
- One may regard this as further evidence that Wt and $t\bar{t}$ should be regarded as separate production modes where possible, due to importance of NLO corrections.
- Alternatively: calculate $WWb\bar{b}$ at NLO, interfaced with a parton shower.

Ht production

- Charged Higgs bosons occur generically in extensions to the Standard Model.
- Examples: MSSM or (more generally) two-Higgs doublet models (type I or type II).
- Charged Higgs bosons can be produced with a top quark, by direct analogy with Wt production.
- Unlike Wt production, there are two kinematic regimes:
    1. $m_{H^-} > m_t$: $H^- t$ production mode is dominant in e.g. MSSM.
    2. $m_{H^-} < m_t$: $H^- t$ interferes with $t\bar{t} \rightarrow tH^- b$.
- In considering NLO corrections to $H^- t$ production, the interference problem can be dealt with using similar methods to those used for Wt.
- From now on, results will focus on high m_{H^-} region.

Ht production in MC@NLO

- $H^- t$ production has been implemented in MC@NLO.
- Will be included (with spin correlations) in next public release.
- Also being implemented in POWHEG (Weydert et. al.).
- Calculation is described in arXiv:0912.3430 (for both low and high Higgs mass).
- Uses five-flavour scheme (as for Wt production).
- NLO is basically identical to Prospino 2.1 (Plehn) $\Rightarrow$ should get same total rate.
- Some example physics results are also presented in the paper...

Results for Ht production

- Previous studies have suggested that additional b jets (i.e. not from top decay) can be used to design $H^- t$ event selection criteria.
- Relies on assumption that additional b jets have sufficiently different properties to radiated light jets.
- The advantages of investigating this assumption in an MC@NLO (or POWHEG) framework are clear:
    1. NLO matrix element gives correct LO description of additional radiation.
    2. Parton shower gives realistic number of final state particles / jet substructure.
- How do the properties of b and light jets compare in $H^- t$ production?

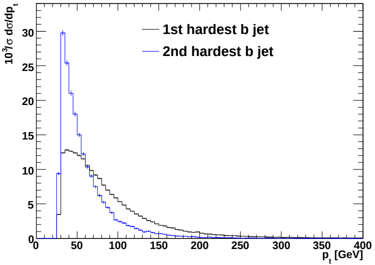
Properties of b and light jets

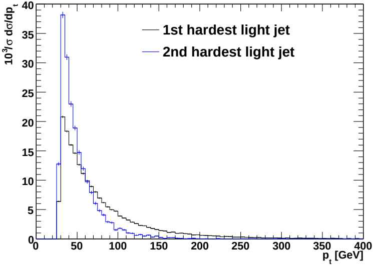
- We wish to compare the *second hardest b* jet with the hardest light jet.
- I.e. the hardest b jet is most likely to have come from the top decay.
- If the properties of the additional b and hardest light jet are different, this can be used to design efficient event selection criteria.
- We consider jets from the k_T algorithm in volume

$$|\eta| < 2.5, \quad p_T > 25 \text{ GeV}.$$

- Also consider leptonic top decay and $m_{H^-} = 300\text{GeV}$.

Properties of *b* and light jets





- The additional *b* jet is not very different to the hardest light jet.
- Similar results observed for other Higgs masses.

Properties of b and light jets

- More quantitatively, one may consider the following question:

  Given that one hard b jet has been observed, what is the probability that that one finds a second b jet by asking for the two hardest jets in the event?

- We find this to be $\simeq 35\%$ for leptonic top decays. For hadronic decays, the results are even worse ($\simeq 12\%$).
- Suggests that it is difficult to use hardness properties of b jets for event selection.
- However, only a rough study (i.e. to illustrate application of MC@NLO).
- For a fuller discussion, see arXiv:0912.3430.

Summary

- Describing Wt is difficult due to interference issues with $t\bar{t}$.
- However, can be implemented in an NLO + shower framework in a gauge-invariant way. Has been implemented in MC@NLO (+ POWHEG?).
- Allows inclusion of NLO corrections in both Wt and $t\bar{t}$ processes.
- Separating Wt from $t\bar{t}$ appears to be justified for Wt and $H \to WW$ signal cuts.
- If unsure for other analyses, use both DR and DS MC@NLO codes.
- $H^- t$ production also implemented.
- Interference issues can be dealt with similarly to Wt.
- Example results for b and light jet properties...