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Wt production at the LHC

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Theory Experiment Interplay at the LHC - April 9 2010

Overview

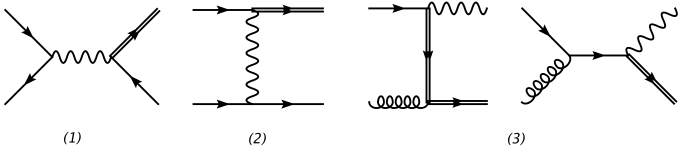
What is the best description of Wt production?

- Single top production modes.
- Interference problem - Wt and $t\bar{t}$.
- Comparison of different theoretical approaches.
- $H \rightarrow WW$ production.
- Outlook

Top physics

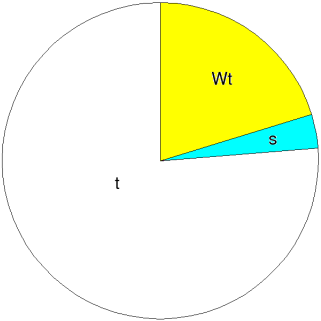
- Mass of top quark $\simeq$ energy scale of electroweak symmetry breaking.
  $\Rightarrow$ Top quark sector can be a sensitive probe of new physics effects.
- The LHC is a "top quark factory" - can produce in $t\bar{t}$ pairs, or singly (t or $\bar{t}$).
- Single (anti-)top production particularly useful in probing electroweak interactions.

Single top production modes



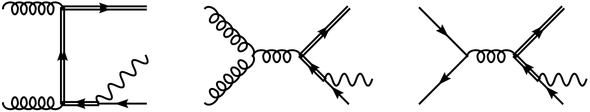
- Three modes of single top production at LO - s channel; t channel; Wt channel.

- Total LHC cross-section $\sim$ 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 $t\bar{t}$.

How do we get the best description of $Wt + t\bar{t}$ production?

Incoherent

- Consider Wt and $t\bar{t}$ as separate processes.
- Interference not present in the sum.
- Need a definition of Wt.
- Also need a way of measuring size of interference.

Coherent

- Consider only final states $WWb\bar{b}$ etc.
- Combine all diagrams, including interference.
- No longer makes sense to think of "Wt" or "$t\bar{t}$".
- NLO corrections to $t\bar{t}$ not included.

- Which description to use is equivalent to the question: Which is bigger - interference effects, or NLO corrections to $t\bar{t}$?
- First, let's see examples of how to implement the above...

Incoherent description of Wt production

- Wt interferes with $t\bar{t}$ at NLO (for the former process).
- Any calculation of Wt at this order must give some prescription for defining it (Zhu, Campbell, Tramontano).
- A definition has also been given in an NLO + parton shower context (Frixione, Laenen, Motylinski, Webber, White).
- This has been implemented in MC@NLO.
- In fact there are two Wt definitions, whose difference measures the interference with $t\bar{t}$.
- The definitions are called diagram removal (DR) and diagram subtraction (DS).

DR & DS - Summary

Diagram Removal

- $t\bar{t}$ removed at amplitude level.
- Diagrams containing $t\bar{t}$ pair not included.
- Defined fully exclusively, at any order.

Diagram Subtraction

- $t\bar{t}$ removed at cross-section level.
- Based on narrow width approximation.
- Defined fully exclusively, at any order.

- Both definitions have been implemented in the MC@NLO program (latest release v3.3).
- Spin correlations also implemented (Frixione, Laenen, Motylinski, Webber).
- Can be used to test the accuracy of the incoherent approximation.

- There are two main contexts in which one needs to model $Wt + t\bar{t}$.
- Firstly, when Wt production is a signal, and $t\bar{t}$ a (significant background).
- Secondly, when both Wt and $t\bar{t}$ are backgrounds to a third process e.g. $H \rightarrow WW$.
- In both cases, accurate predictions are essential.
- Suggests we want to include NLO corrections to $t\bar{t}$ i.e. to use the incoherent approximation.
- Is this justified? Can find out by using DR and DS modes in MC@NLO.
- Let's consider Wt production and $H \rightarrow WW$ in turn.

Wt production as a signal

- Aim: To show that DR and DS give similar results for *Wt* production, when *Wt* signal cuts are used.
- 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

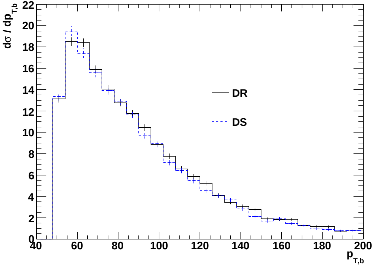
- Have evaluated DR and DS cross-sections for a variety of choices of b-tagging efficiency (e_b) and light jet rejection rate (r_{lj}):

e_b	r_{lj}	σ^{DR}_{Wt}/pb	σ^{DS}_{Wt}/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.

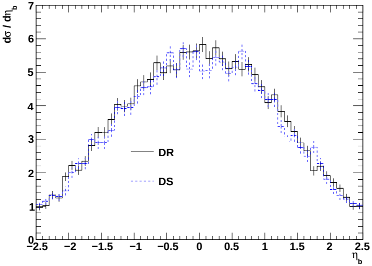
$\Rightarrow$ Wt is indeed a well-defined signal!

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.



Top production as a background - $H \to WW$

- If the Higgs mass is intermediate (150 GeV $\lesssim m_H \lesssim$ 180 GeV), the only viable discovery channel is via decay to two W bosons.
- Top production ($Wt + t\bar{t}$) is a significant background, as is non-resonant W pair production.
- Spin correlations can be used to reduce the backgrounds (Dittmar, Dreiner).
- It is clearly very important that estimates of the top production background are accurate.
- Can the incoherent approximation be used for Higgs signal cuts?

Higgs signal cuts

- Aim: Look at $Wt+t\bar{t}$ production for Higgs signal cuts, and check that interference is small.
- We used the following (based on Anastasiou, Dissertori, Stockli):
  1. Two opposite sign leptons with $p_T > 25$ GeV and $|\eta| < 2.5$. Also, their invariant mass should satisfy 12 GeV$< m_{ll} <$40 GeV.
  2. The azimuthal angle between the leptons should satisfy $\phi_{ll} < \pi/4$.
  3. Highest lepton p_T should be between 30 GeV and 55 GeV.
  4. Missing transverse energy $E_T^{miss} > 50 GeV$.
  5. No jets (b or light) with $p_T > 25$ GeV and $|\eta| < 2.5$.

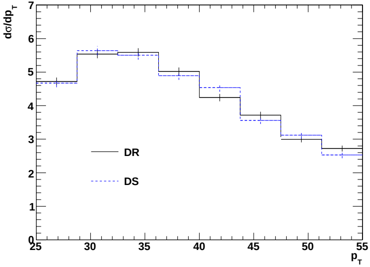
Higgs signal cuts - results

- With these cuts, find:

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

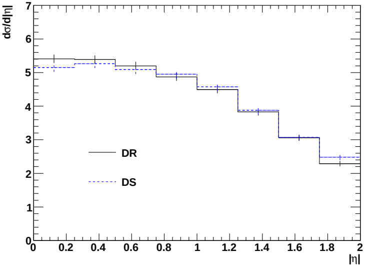
- DR and DS results are identical within statistical uncertainties.
- Wt and $t\bar{t}$ production backgrounds are comparable in size, and a significant fraction of the signal.

Higgs signal cuts - results



- Here we show the transverse momentum and |pseudo-rapidity| of the lepton from the top.

- Again, interference is small locally in phase space.

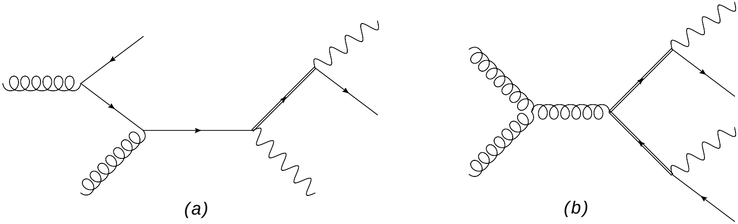


Coherent approach

- We have seen that the incoherent approximation is justified for Wt production and $H \to WW$.
- There may still be cases, however, where neglecting interference with $t\bar{t}$ production is not justified.
- Furthermore, it is interesting to compare the MC@NLO calculation with a description in which all interference terms are explicitly included, but NLO $t\bar{t}$ corrections are not.
- Let's look at this in more detail...

$Wt + t\bar{t}$ - coherent description

- If interference cannot be neglected, it no longer makes sense to think of separate Wt and $t\bar{t}$ processes.
- Instead, one considers given final states.
- For $Wt + t\bar{t}$ production, it is easiest to work in a four flavour scheme (no initial state b quarks).
- Then the relevant final state is $WWb\bar{b}$, and one has singly and doubly resonant diagrams:



(a) (b)

Coherent Approach

- For a fair comparison with the MC@NLO approach, one can interface the tree-level diagrams with a parton shower.
- Matching (CKKM, MLM) is not needed in the four-flavour scheme at this order.
- We generated matrix elements using MadGraph, and interfaced these with HERWIG (same parton shower as MC@NLO).
- All interference effects are now explicitly included.
- How does the approach compare with the incoherent MC@NLO decription?

Comparison of coherent and incoherent approaches

- One way of comparing the two descriptions is to calculate total cross-sections and distributions for various signal cuts.
- If the K-factors $(= \sigma^{NLO}/\sigma^{LO})$ are different for different analysis cuts, then NLO is not a simple rescaling of the LO result.
- Also suggests that they should really be regarded as separate processes.
- Aswell as the Wt and $H \to WW$ cuts presented earlier, one may also consider top pair signal cuts:
  1. One electron or muon with $p_T > 20$ GeV.
  2. Missing transverse energy $E_T^{miss} > 20$ GeV.
  3. At least four jets with $p_T > 20$ GeV.
  4. At least three jets with $p_T > 40$ GeV.
  5. All leptons and jets to satisfy $|\eta| <2.5$.

K factors for different cuts

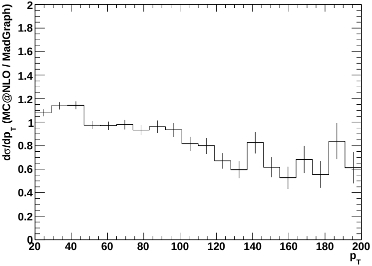
- We obtain results for $Wt + t\bar{t}$ (or $WWb\bar{b}$) production for the three choices of cuts.
- For each choice ,the K-factor is defined as the ratio of the MC@NLO and (MADGRAPH+HERWIG) cross-sections.

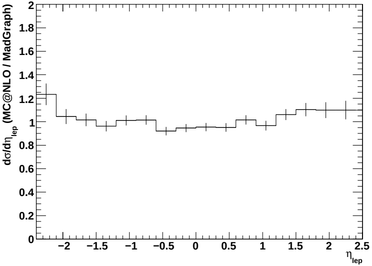
Signal cuts	K-factor
Top pair	1.508 ± 0.012
Wt	1.345 ± 0.028
$H \to WW$	1.98 ± 0.07

- DR used for the Wt component in MC@NLO (DS gives the same within errors).
- K-factors are completely different!

Distributions

- Also some shape differences in distributions.





- E.g. p_T and η of the final state lepton for $t\bar{t}$ cuts.

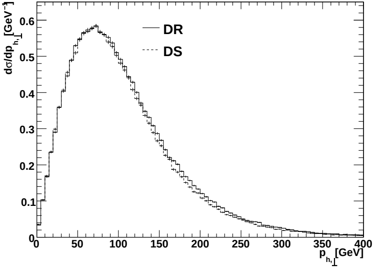
Discussion

- Have compared two calculations for $Wt + t\bar{t}$ production.
- One has NLO corrections to $t\bar{t}$ production, but no interference between Wt and $t\bar{t}$.
- The other includes all interference, at the expense of NLO corrections to $t\bar{t}$.
- The two descriptions are fundamentally different, in that the K-factors are different for different analysis cuts.
- Also differences in shapes of distributions.
- Suggests that Wt and $t\bar{t}$ should be regarded as separate processes where possible.
- NLO $t\bar{t}$ corrections are, in a well-defined sense, larger than interference effects.

Other processes

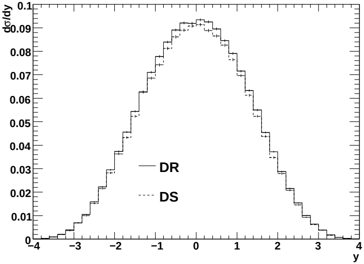
- Similar interference problems occur in other contexts.
- An obvious one is charged Higgs boson production in association with a top quark.
- One can use similar methods to the Wt case for analysing the impact of interference effects.
- $H^{-}t$ production has been implemented using the DR and DS definitions in MC@NLO (Weydert et. al.).

Sample results for $H^{-}t$ production



- Shown are the p_t and y distributions for the charged Higgs.

- DR and DS agree with suitable cuts - thus incoherent approximation is valid.



Conclusions

- Have considered Wt production at the LHC.
- Non-trivial at NLO and beyond due to interference with top pair production.
- Either one cannot regard Wt and $t\bar{t}$ as separate processes, or one can add them incoherently - provided one can justify this.
- Have shown that for Wt and $H \rightarrow WW$ cuts, the incoherent approximation is justified.
- Comparison with a coherent approach shows that NLO corrections to $t\bar{t}$ are important.
- Need separate K-factors for Wt and $t\bar{t}$.
  $\Rightarrow$ Incoherent approximation should be used where possible.
- Similar conclusions hold for other processes.