Single top computations and generation tools

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Top 2014, Cannes, Sep. 29th 2014
Single-top: EW production of tops

Two main production mechanism of tops at hadron colliders:

Focus of this talk

This Morning

Probe strong interactions

Probe weak interactions
Disclaimer

Extremely biased selection of topics

• Time constraints ->
  presenting everything neither possible nor useful

• Personal expertise ->
  won’t discuss at all parton-shower issues,
  although of course very interesting and important
LHC as a top factory

Figure 2. NLO inclusive cross sections for single and top quark pair production with and without an accompanying Z boson. The NLO $t\bar{t}Z$ cross section is estimated from the lowest order result using a $K$-factor of 1.39 and renormalization and factorization scales $\mu = m_t + m_Z/2$.

We consider the full process (and similarly for the charge conjugate process),

\[ u + b \rightarrow t + Z + d \]

\[ \rightarrow \nu + e^+ + b \]

where the leptonic decay of the top quark is included and we have specified the charged leptons that are associated with the $Z$ decay. The top quark decay is included using the techniques described in Refs. [9–11] and retains all spin correlations at the expense of requiring the top quark to be on-shell. Since this calculation involves an incoming $b$-quark, it is necessarily a five-flavor calculation.

We have also considered the closely-related single top + $H$ process which is of smaller phenomenological interest in the Standard Model. A brief description of the next-to-leading order result is given in Appendix B.

[Campbell, Ellis, Rontsch (2013)]

From discovery to PRECISION PHYSICS
The classical picture: 3 production mechanism

**T-CHANNEL**

LHC8: ~ 82%
TEV: ~ 65%

**ASSOCIATED PRODUCTION**

LHC8: ~ 15%
TEV: ~ 0

**S-CHANNEL**

LHC8: ~ 5%
TEV: ~ 33%

Good for the old ‘pioneering’ days, must be taken with care for precision physics
t- vs s- channels: it still makes sense

In principle: beyond LO t- and s- channels same initial/final states -> interferences, no well defined distinction

However in practice:
• interference starts at NNLO (in the 5FNS)
• suppressed (color / kinematics)

Can still talk meaningfully about T (and S) Channel
Talking about fiducial cross section is much better
Ideally for realistic final states
The quest for precision: t-channel @ NNLO

[Brucherseifer, FC, Melnikov (2013)]
t-channel single top: do we need NNLO?

Look at the NLO prediction

The total cross section at the 8 TeV LHC:

\[ \sigma_{LO} = 53.77 + 3.03 - 4.33 \text{ pb} \]
\[ \sigma_{NLO} = 55.13 + 1.63 - 0.90 \text{ pb} \]

Naively:

“Small ~ 2% corrections, no need to go further”

However…
t-channel single top: do we need NNLO?

The total cross section at the 8 TeV LHC: A Closer Look

\[ \sigma_{\text{LO}} = 53.77 + 3.03 - 4.33 \text{ pb} \]

\[ \sigma_{\text{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb} \]

Large cancellations among channels
t-channel single top: do we need NNLO?

The NLO K-factor is accidentally small

The pattern of cancellation is (very) phase-space dependent:

\[ \sigma(p_{\perp}, t > p_{\perp, \text{cut}}) \]

<table>
<thead>
<tr>
<th>( p_{\perp} )</th>
<th>( \sigma_{\text{LO}}, \text{pb} )</th>
<th>( \sigma_{\text{NLO}}, \text{pb} )</th>
<th>( \delta_{\text{NLO}} )</th>
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<tr>
<td>0 GeV</td>
<td>53.8^{+3.0}_{-4.3}</td>
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<tr>
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Corrections to more exclusive observables \( \sim 10\% \)
T-channel single top: do we need NNLO?

The total cross section at the 8 TeV LHC: a CLOSER LOOK

\[ \sigma_{\text{LO}} = 53.77 + 3.03 - 4.33 \text{ pb} \]
\[ \sigma_{\text{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb} \]

- Scale variation similar to corrections
- \( \sim \) percent difference between 4FNS/5FNS calculations
T-channel single top: \textbf{do we need NNLO?}

The total cross section at the 8 TeV LHC: \textbf{a Closer Look}

\[ \sigma_{\text{LO}} = 53.77 + 3.03 - 4.33 \text{ pb} \]
\[ \sigma_{\text{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb} \]

- Large (accidental?) cancellations between channels
- Scale variation (\textit{\sim} NNLO!) as large as corrections
- Larger corrections for more exclusive observables

To control single-top production at the percent level:
\textbf{NNLO Correction to t-channel Production}
Anatomy of a NNLO computation

• For a long time, the problem of NNLO computations was how to consistently extract IR singularity from double-real emission/real-virtual emission.

• This problem has now been solved both in theory (antenna subtraction, sector decomposition+FKS, semi-analytic subtraction) and in practice (top-pair, dijet, H+jet,…).

• Now the problematic part is computing two-loop amplitudes. State of the art:
  • Numerically: 2->2 with 1 extra mass-scale (tt)
  • Analytically: 2->2 with two external mass scales (VV*)
Recent developments in NNLO techniques, allowed us to compute (almost) \textit{t-channel single-top} corrections.

In particular, for our computation:

- \textbf{5FNS@NNLO (2->2)} (although almost all nice features of 4FNS@NLO naturally inherited)

- Fully differential (arbitrary cuts on the final state are not a problem)

- For now, top is stable but very easy to implement top decay in the NWA with full spin correlation
Single-top in the ‘factorized’ approximation

Two-loop amplitudes:

- Trivial ($\sim NLO^2$)
- Simple
- (~OK)
- (very) hard

Must be interfered with tree-level -> **COLOR SINGLET**

The ‘hard’ amplitude contribution is **suppressed by** $1/N_c^2$

**NEGLECTED IN OUR COMPUTATION**

[same for s/t interference]
Single-top @ NNLO: total cross section

8 TeV LHC, MSTW2008, $m_t = 173.2$ GeV

$$\sigma_{\text{LO}} = 53.8^{+3.0}_{-4.3} \text{ pb} \quad \sigma_{\text{NLO}} = 55.1^{+1.6}_{-0.9} \text{ pb}$$

$$\sigma_{\text{NNLO}} = 54.2^{+0.5}_{-0.2} \text{ pb}$$

$(\mu_R=\mu_F= \{m_t/2, m_t, 2 m_t\})$

- Still delicate interplay/cancellations between different channels $\rightarrow$ important to consistently compute corrections to all of them
- Result very close to the NLO (-1.6%), reduced $\mu$ dependence $\rightarrow$ good theoretical control
- $\mu$ dependence dominated by factorization scale (larger scale $\rightarrow$ more b)
Single-top @ NNLO: more differential observables

<table>
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<tr>
<th>$p_\perp$ (GeV)</th>
<th>$\sigma_{\text{LO}}, \text{pb}$</th>
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<th>$\delta_{\text{NLO}}$</th>
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<td>+4.9%</td>
<td>48.3^{+0.3}_{-0.02}</td>
<td>−1.2%</td>
</tr>
<tr>
<td>40</td>
<td>33.4^{+1.7}_{-2.5}</td>
<td>36.5^{+0.6}_{-0.03}</td>
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<td>+13.6%</td>
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<td>+1.6%</td>
</tr>
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- Contrary to NLO, results stable in the full spectrum
- Scale dependence typically improved
- K-factor is small but not constant
Very similar results for anti-top

$$\sigma_{\text{NNLO}, \bar{t}} = 29.7^{+0.3}_{-0.1} \text{ pb}$$

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<th>$\sigma_{\text{NLO}}, \text{ pb}$</th>
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<tr>
<td>0 GeV</td>
<td>29.1$^{+1.7}_{-2.4}$</td>
<td>30.1$^{+0.9}_{-0.5}$</td>
<td>+3.4%</td>
<td>29.7$^{+0.3}_{-0.1}$</td>
<td>−1.3%</td>
</tr>
<tr>
<td>20 GeV</td>
<td>24.8$^{+1.4}_{-2.0}$</td>
<td>26.3$^{+0.7}_{-0.3}$</td>
<td>+6.0%</td>
<td>26.2$^{+0.01}_{-0.1}$</td>
<td>−0.4%</td>
</tr>
<tr>
<td>40 GeV</td>
<td>17.1$^{+0.9}_{-1.3}$</td>
<td>19.1$^{+0.3}_{+0.1}$</td>
<td>+11.7%</td>
<td>19.3$^{+0.2}_{+0.1}$</td>
<td>+1.0%</td>
</tr>
<tr>
<td>60 GeV</td>
<td>10.8$^{+0.5}_{-0.7}$</td>
<td>12.7$^{+0.03}_{+0.2}$</td>
<td>+17.6%</td>
<td>12.9$^{+0.2}_{+0.2}$</td>
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• NLO corrections slightly larger, NNLO very similar

• Slightly larger scale variation w.r.t top, NLO scale variation accidentally small
top/anti-top ratio very stable

8 TeV LHC, MSTW2008, $m_t = 173.2$ GeV

$$\sigma_{t,\text{LO}}/\sigma_{\bar{t},\text{LO}} = 1.85$$

$$\sigma_{t,\text{NLO}}/\sigma_{\bar{t},\text{NLO}} = 1.83$$

$$\sigma_{t,\text{NNLO}}/\sigma_{\bar{t},\text{NNLO}} = 1.83$$

No substantial modification w.r.t. NLO
NNLO is ready for serious phenomenology

Easy to do:

- complete error estimates (PDF, $\mu_R/\mu_F$)
- $m_b$ effects from PDF evolution
- 7/8/13 TeV ratios
- run with fiducial cuts on the reconstructed top system
- differential distributions at the reconstructed level?

Known in principle (but some work involved):

- interface with top decay in the NWA
- decay@NNLO is known [Gao, Li, Zhu (2012); BCM (2013)]
- realistic final state description@NNLO
A step towards reality: top decay
Top quark decay in single-top predictions

- Top: narrow resonance, decay before hadronization
- To reduce reconstruction biases, it is important to properly include top decay in the theory prediction
- From tt studies, we know consistent treatment of QCD corrections for production and decay is important

- Full computation of pp→WbX much more complicated than pp→tX
- However, $\Gamma_t/m_t << 1$, so (for inclusive enough observables) the situation can be significantly simplified by using the narrow-width-approximation
  - QCD corrections to production/decay do not talk
  - Still, full spin information is retained
  - Error of the NWA parametrically suppressed by $\Gamma_t/m_t$

[Fadin, Khoze, Martin (1994)]
Validating the NWA

For benchmark process (t-channel single top), we now have the tools for validating the NWA at NLO

[First pioneering studies: s-channel, Pittau (1996)]

Three increasingly accurate predictions for single top @ NLO

• NWA, NLO in production and decay, $p_t^2 = m_t^2$
  [Campbell, Ellis (2012)]

• EFT for top decay: $p_t^2 \sim m_t^2$
  [Falgari, Mellor, Signer (2010)]

• Full off-shell effects, $\sim$Wbj final state, $p_t^2$ generic
  [Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]

![Diagrams](image-url)
How well does the NWA work?

In general, the NWA works extremely well, as expected. 

[Table 3: LHC (8 TeV) cross sections for the process defined via the analysis of Table 1, at LO and NLO for the o-shell (CMS), NWA and ET computations. Numbers in brackets are Monte Carlo integration uncertainties whilst the percentages indicate scale uncertainties. ‘%di' is the difference to the CMS results.]

Figure 4: Transverse momentum of light jet, $p_T(J_{\text{light}})$.

Figure 6: Transverse momentum of $b$-jet relative to flight of top quark, in reconstructed top quark rest frame, $p_T(J_b)_{\text{rel.t.}}$

4. Conclusions

In this letter we have performed the computation of NLO QCD corrections to EW $t$-channel $W^+b$ production. The calculation, carried out within the aMC@NLO framework, was done making use of the complex-mass scheme, and retains the full o-shell and interference effects at NLO. In addition we have compared our results with those obtained with the NWA and ET approaches. We conclude that, at least in the case of the top quark, it is incorrect to claim that the NWA is an excellent approximation universally. While the NWA gives a good description of many observables, it fails dramatically for others, in particular those sensitive to the invariant mass of the $(W^+,J_b)$-system. On the other hand, we find that the predictions of the ET approach are much closer to those of the full NLO QCD results. These two facts combined imply that for certain observables o-shell effects are much more relevant for a correct description of the final-state kinematics, than NLO corrections to the top-quark decay alone (which include hard radiation o-the $b$ quark). We feel that this is a general conclusion.

[Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]
However, be careful

By definition, NWA is not supposed to work:
- for observables sensitive to $M_{Wb}$
- beyond kinematics edges

And indeed it does not
Top decay, recap:

Thanks to advances in NLO tools, one can validate the NWA approximation on benchmark processes -> **WORKS EXACTLY AS EXPECTED**

Pioneering studies [s-channel, Pittau (1996)] confirmed

[Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]

Can confidently use NWA to compute (parton level) predictions with realistic final states for complicated processes

- NNLO
- single-top + X (see e.g. arXiv1302.3856 and talk on Thursday)

If NWA is not supposed to work for your observable:

- EFT seems to work pretty well
- NLO tools could provide full predictions in the near future
Top decay: interfacing with PS

- Ideally, one wants hadron-level results
- PS with decaying resonances seems tricky
  [see e.g. Stefan Prestel’s talk at this conference pre-meeting]

[A. Papanastasiou, TOP LHC WG meeting]

**Ongoing work, stay tuned!**
Wt vs WWbb
[see also J. Winter’s talk this afternoon]
The classical picture: 3 production mechanism

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LHC8: ~ 82%
TEV: ~ 65%

ASSOCIATED PRODUCTION
LHC8: ~ 15%
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Is there ACTUALLY a problem with this picture?
Yes: $Wt$ vs $WWbb$

Already at NLO, $Wt$, ttbar and ‘background’ share the same initial/final states -> interferences, cannot be separated

If you want to consider massive $b$ (good reasons to do it) and work in the 4FNS -> LO problem

In the past, full computation was out of question -> must cook up some add-hoc recipe to deal with it (DR,DS,PR…) None of them is Theoretically Fully Sound
Wt and \( \bar{t}t \): unified description

Thanks to modern tools the full (very hard) NLO computation with massive b is now doable

[Frederix (2013), Cascioli, Maierhoefer, Kallweit, Pozzorini (2013)]

- There is no need (nor reason) to use old strategies any more
- Wt: single resonant contribution of the full process -> enhanced/suppressed with specific cuts
- Again, matching with PS is subtle (under investigation)
Example: Wt/tt as background for H→WW

[Frederix (2013), MadGraph5/aMC@NLO]

- H→WW, 1-jet bin, ATLAS cuts
- ‘Large tt background, ~20% Wt’ -> same process

\[ m_{ll}: \text{shape distortion @ NLO} \]
Example: separating $tt$
[Cascioli, Maierhoefer, Kallweit, Pozzorini (2013), OpenLoops]

Theoretically sound procedure to remove NWA $tt$ contribution from $Wt$/off-shell effects

- Non $tt$ effects very jet-bin dependent, concentrated in the 0/1 jet bins
- Large in phase space regions with unresolved b-quarks
- Non $tt$ effects perturbatively stable
- Nice interplay of NLO / $Wt$ and off shell effects

$p_T, j = 30$ GeV

NLO(LO) 4F NNPDFs
Conclusions

Advances in theory and phenomenology bring predictions closer and closer to experimental reality

- Precision -> fully differential NNLO
  - Corrections as large as NLO on the total rate
  - Differential K-factor non trivial shape, but small
  - Will be interesting to let the top decay (and PS…)

- Realistic final states -> top decay
  - NWA validated by dedicated benchmark computations
  - For simple processes, can go beyond NWA if needed
  - Conceptual work needed for proper PS matching

- Artificial distinctions no longer needed -> Wt vs WWbb
  - Unified description for top as background
  - Theoretically correct separation of tt
  - Again, improvements needed for PS
Thank you for your attention!