

Theoretical status of single top and top associated production predictions

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In this talk the recent progress in theoretical developments for single top production and top pair production in association with heavy vector bosons is reviewed. For top pair associated production, particular emphasis is put on complete-NLO predictions, i.e. predictions including all LO and NLO contributions in an expansion in both the strong and the electroweak couplings. For single-top production the three most relevant results that appeared this year are summarized.

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1. Introduction

In the quest for understanding the Standard Model (SM) of particle physics, and possibly finding the physics beyond it, careful comparisons between experimental data and theoretical predictions need to be made. In particular, with the constantly growing, highly accurate data sample at the LHC, more and more SM process can be measured with high accuracy. Most exciting in this context is the measurement of Higgs boson production in association with the top quark pair, announced at this conference [1, 2]. This confirms that the Higgs couples strongly to the top quark and is most-likely (at least to a certain extend) responsible for the generation of its mass. Cross sections of similar size have been measured for the production of a top quark pair in association with a heavy vector boson [3, 4]. Indeed, these measurements can be used to measure the top quark coupling to the Higgs and Z boson.

The third heavy boson in the SM, the W^\pm boson, couples also to the top quark. To measure its coupling one has to look at single top quark production, because a quark changes flavour when exchanging a W^\pm boson, and therefore is typically not produced in pairs. The single top quark production was first measured at the Tevatron [5, 6], but recently the first differential distributions have appeared at the LHC [7, 8].

In order to make definite conclusions from the measurements of these processes, they need to be interpreted within a theory model. In particular, if we could find an inconsistency between the SM and these measurements we would have a clear signal for the need of New Physics. To get the most out of the measurements in this context, highly accurate predictions for these processes within the SM are required. In this talk, the latest developments in the predictions for the top associated production processes as well as the single-top production mechanisms are presented.

2. Top associated production with a heavy vector boson

Even at next-to-leading order (NLO) in the strong coupling the total cross section for production of top–anti-top quark pair together with a heavy boson has a relatively large perturbative uncertainty from renormalisation and factorisation scale dependence – of the order of 10-15% at the 13 TeV LHC. It would therefore be interesting to compute also the next order (NNLO) in the strong coupling to reduce this uncertainty. However, since this has already been a formidable task for top pair production (without the extra, heavy boson) [9], the complete NNLO calculation for $t\bar{t}H$, $t\bar{t}Z$ and $t\bar{t}W^\pm$ production are completely out of reach with current technology.

On the other hand, certain subsets of the higher order corrections are known at all orders in perturbation theory. In particular, since these processes feature relatively heavy particles in the final state, with a total invariant mass typically 600-700 GeV, it can be expected that effects due to being forced to be relatively close to that invariant mass threshold, because there is not much energy left in the collision to produce hard radiation in association with the core process, is a dominant contribution to higher order corrections. Indeed, recently these so-called threshold logarithms have been resummed to all orders in perturbation theory up to next-to-next-to-leading logarithmic (NNLL) accuracy, including their consistent matching to the full NLO results [10, 11, 12, 13]. Including these all-order terms reduces the scale dependence by 30-50%, as can be seen in table 1.

pert. order	process	PDF order	σ [fb]
NLO	$t\bar{t}H$	NLO	$474.8^{+47.2}_{-51.9}$
NLO+NNLL	$t\bar{t}H$	NNLO	$486.4^{+29.9}_{-24.5}$
NLO	$t\bar{t}W^+$	NLO	$356.3^{+43.7}_{-39.5}$
NLO+NNLL	$t\bar{t}W^+$	NNLO	$341.0^{+23.1}_{-13.6}$
NLO	$t\bar{t}W^-$	NLO	$182.2^{+23.1}_{-20.4}$
NLO+NNLL	$t\bar{t}W^-$	NNLO	$177.1^{+12.0}_{-6.9}$
NLO	$t\bar{t}Z$	NLO	$728.3^{+93.8}_{-90.3}$
NLO+NNLL	$t\bar{t}Z$	NNLO	$777.8^{+61.3}_{-65.2}$

Table 1: Total cross sections in fb for the LHC at 13 TeV. Table taken from ref. [14]

With the uncertainties well below 10%, one might wonder if electroweak (EW) corrections play a significant role in these processes. At the level of total rates, it can be expected that the NLO_1 (the NLO QCD corrections), are the largest followed by NLO_2 (the NLO EW corrections), NLO_3 and finally NLO_4 —see fig. 1 for details on the naming convention for the corrections. On the other hand, in tails of distributions, where EW Sudakov logarithms can become sizeable, the NLO_2 term typically dominates over the NLO_1 corrections.

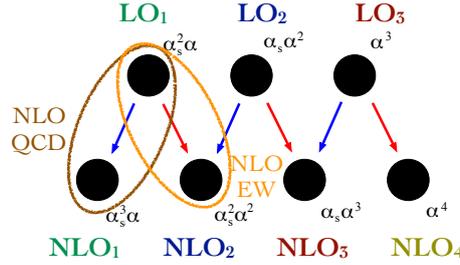


Figure 1: Naming conventions for the various contributions with fixed α_s and α coupling combinations to $t\bar{t} + Z/W^\pm/H$. Including all these contributions is referred to as “complete-NLO” predictions.

At the level of total rates the above reasoning on the size of the corrections holds pretty much for the $t\bar{t}Z$ and $t\bar{t}H$ processes, see tab. 2. Also at the level of differential distributions, the size of the contributions to the complete-NLO computation behave as expected for these two processes. See for example the left hand plot of fig. 2 for the various LO and NLO contributions to the transverse momentum of the Higgs boson in $pp \rightarrow t\bar{t}H$ production.¹ On the other hand, for the $t\bar{t}W^\pm$ processes, there is a surprise: the NLO_3 terms is more than an order of magnitude larger than one would expect from the sizes of the EW and QCD coupling strengths, see tab. 2 and the right hand plot of fig. 2. The origin of these large corrections can be pointed to the opening of $tW \rightarrow tW$ scattering in the NLO_3 contributions [16]. This is not the only process for which it is known that the subleading NLO_i terms are larger than expected [16, 17]. In particular for 4-top production, the NLO_2 and NLO_3 contributions are individually quite large, easily surpassing 10-15% (depending on the scales used), but come with opposite signs. However, when taken together their sum reduces

¹Very recently, in ref. [15] the NLO QCD and EW corrections to this process, including the top quark decays and off-shell effects have been considered.

	$pp \rightarrow t\bar{t}Z$	$pp \rightarrow t\bar{t}W^+$	$pp \rightarrow t\bar{t}H$
LO ₁	$5.0463 \pm 0.0003 \cdot 10^{-1}$ pb	$2.4116 \pm 0.0001 \cdot 10^{-1}$ pb	$3.4483 \pm 0.0003 \cdot 10^{-1}$ pb
LO ₂	-0.691 ± 0.001 %	$+0.000 \pm 0.000$ %	$+0.406 \pm 0.001$ %
LO ₃	$+2.259 \pm 0.001$ %	$+0.962 \pm 0.000$ %	$+0.702 \pm 0.001$ %
NLO ₁	$+44.809 \pm 0.028$ %	$+49.504 \pm 0.015$ %	$+28.847 \pm 0.020$ %
NLO ₂	-0.846 ± 0.004 %	-4.541 ± 0.003 %	$+1.794 \pm 0.005$ %
NLO ₃	$+0.845 \pm 0.003$ %	$+12.242 \pm 0.014$ %	$+0.483 \pm 0.008$ %
NLO ₄	-0.082 ± 0.000 %	$+0.017 \pm 0.003$ %	$+0.044 \pm 0.000$ %

Table 2: Cross sections for the five $t\bar{t} + X$ processes. The uncertainties quoted are of statistical nature only, originating from the Monte Carlo integration over the phase space. The subleading LO and NLO contributions are given as percentage fractions of LO₁. Table adapted from ref. [18].

to a corrections of around 1% and is almost independent from the scale choice. The origin of this cancelation is currently not understood.

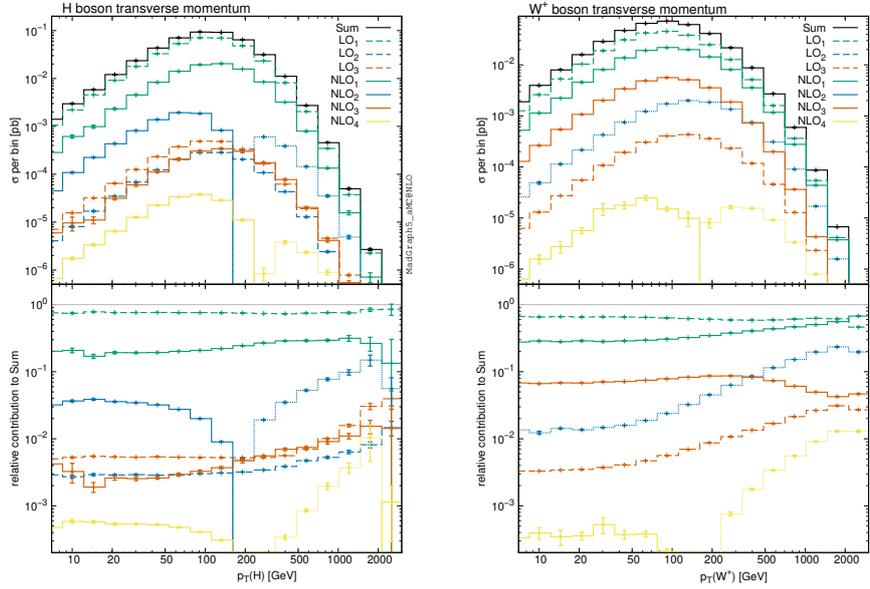


Figure 2: Transverse momenta of the heavy vector boson in $t\bar{t}H$ (left) and $t\bar{t}W^+$ (right) production. Dashed and solid lines denote positive LO and NLO contributions, respectively, while dot-dashed and dotted are the (absolute value of) negative LO and NLO contributions, respectively. Plots taken from ref. [18].

3. t -channel single top production

The three recent developments in single-top production are all related to the largest single top channel, i.e. the production of a single top through a t -channel W -boson exchange.

3.1 Transverse momentum resummation

Earlier this year, predictions in which the transverse momentum logarithms $\log(q_{\perp}/Q)$, with Q the typical hard scale of the single top process and $q_{\perp} = p_T(\text{top} + \text{jet})$, have been resummed to all

orders in perturbation theory up to next-to-leading logarithm (NLL) [19]. These predictions should be superior to other known predictions in the region of phase-space where the combined transverse momenta of the top quark and the hardest jet, q_{\perp} is small. These predictions are compared to predictions obtained with the pythia8 [20] parton shower. For central jets agreement is found in the shape of the q_{\perp} distributions. On the other hand, for very forward jets, the resummed predictions peak at much smaller transverse momenta than the pythia8 predictions, see fig. 3. However, in the pythia8 predictions, the recent improvements regarding initial-final dipoles [21] have not been included. It would therefore be interesting to redo this comparison with the updated pythia8 version.

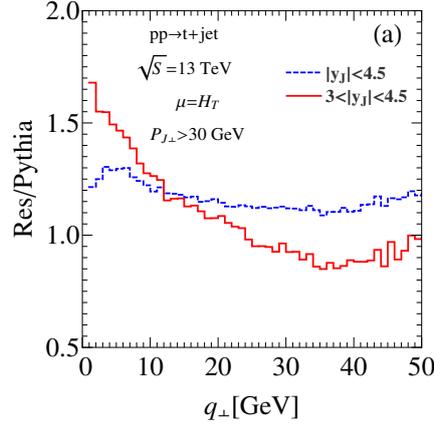


Figure 3: Ratio between the NLL resummed result and the pythia8 predictions for the q_{\perp} distribution. Plot taken from ref. [19].

3.2 NNLO corrections to production and decay

In 2017 Berger et al. published the first NNLO calculation for t -channel single top production where the corrections are included in both the production and the decay [22]. In this calculation interference between the light and heavy quark line, the interference between production and decay and any off-shell effects (for the top quark) are neglected. Earlier this year, they updated their results by including more differential distributions and performing a more complete phenomenological study [23]. One of the most interesting results are that the NNLO corrections can be very large and outside the NLO scale uncertainty band in the case where a jet veto is applied, reducing the LO cross section by almost 40%. This is very relevant due to the fact that such a jet veto is applied in experimental analyses in order to reduce the backgrounds from top pair production [8, 24]. Even though such a jet veto might introduce large logarithms order by order in perturbation theory, there are no signs of a breakdown of perturbation theory in the predictions, e.g. through enhanced scale uncertainty bands at higher orders. On the other hand, it would be interesting to see if such a large reduction in rates due to higher orders is well-modeled by a parton shower.

3.3 Minlo' predictions

The Minlo' method [25, 26, 27] is a way of getting predictions that are simultaneously NLO

accurate for observables differential in a system S and $S + \text{jet}$. In a recent work, this has been applied to t -channel single top production resulting in predictions, that are matched to a parton shower, that have NLO accuracy in the t , $t + \text{jet}$ and $t + 2\text{jet}$ phase-spaces [28]. The numerical Minlo' method used for this process, works by enhancing the NLO+PS predictions for the $pp \rightarrow tjj$ process by a NLL_σ accurate Sudakov form factor, in which an additional term is fitted numerically in such a way that observables inclusive over the 2nd jet are equal to the NLO+PS predictions for $pp \rightarrow tj$. In fig. 4 we show the transverse momentum of the top quark (left) and the jet multiplicity (right). For the transverse momentum of the top quark, the Minlo' predictions (denoted by STJ* in the figure) agree with the NLO predictions for $pp \rightarrow tj$ (denoted by ST). Similarly for the 0 and 1-jet multiplicities. On the other hand, for the 2-jet rate (and beyond) the Minlo' predictions are in agreement with the NLO predictions for the $pp \rightarrow tjj$ process (denoted by STJ in the figure). This method allows for the inclusion of the NNLO corrections, resulting in the current state-of-the-art for fully exclusive predictions: NNLO+PS.

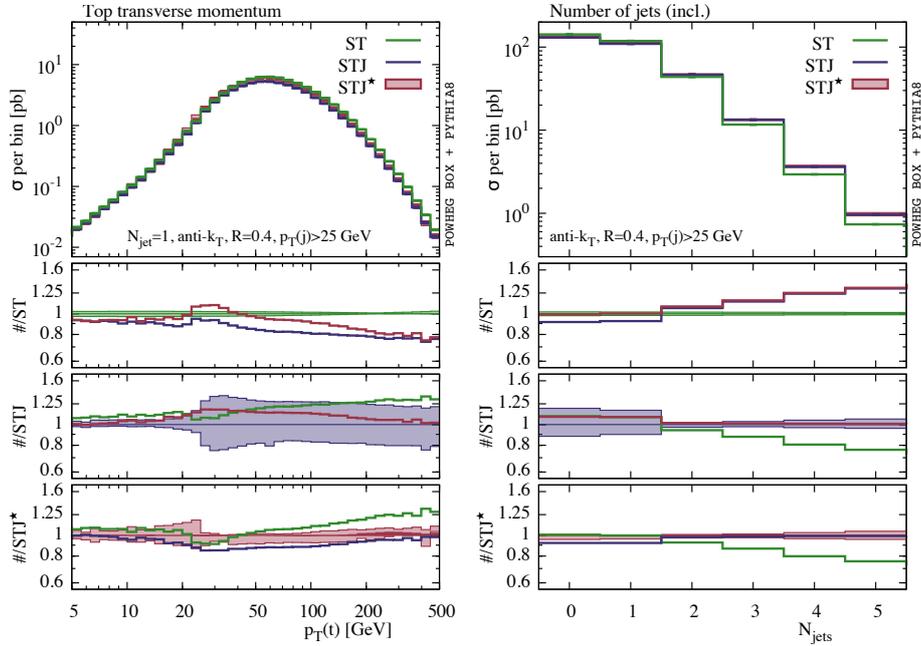


Figure 4: Minlo' predictions for the transverse momentum of the top quark (left) and the jet multiplicity (right). Plots taken from ref. [28].

4. Conclusions

In this talk we have summarised the recent developments in top quark pair associated and single top production. For the top quark associated production processes we discussed the matched predictions in which the NLO corrections have been augmented with the resummation of threshold logarithms up to NNLL accuracy. We also showed that the complete-NLO predictions entail no surprises for $t\bar{t}Z$ or $t\bar{t}H$ production. On the other hand, for $t\bar{t}W^\pm$ the NLO_3 term is much larger than expected, due to the opening of the $tW \rightarrow tW$ scattering contributions.

For single top production, we mentioned the three latest developments: transverse momentum resummation to get highly accurate predictions for the $t + \text{jet}$ small transverse momentum; a more elaborate study on the NNLO predictions for single-top including, the top decay; and the Minlo' predictions for a NLO accurate predictions in both the single top process, as well as this process plus an additional resolved hard jet, without the inclusion of a merging scale.

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