Single-top production in the Standard Model and beyond

Nikolaos Kidonakis

- Higher-order soft-gluon corrections
- $t$-channel and $s$-channel production
- $tW$ production
- $tZ$ production via anomalous couplings
Higher-order corrections

QCD corrections are very significant for single-top production

Soft-gluon corrections are important
and they approximate exact results very well

We calculate/resum these soft corrections at NNLL accuracy
for the double-differential cross section

Finite-order expansions

Approximate NNLO (aNNLO) and N^3LO (aN^3LO) predictions
for cross sections and differential distributions
Soft-gluon corrections

partonic processes

\[ f_1(p_1) + f_2(p_2) \rightarrow t(p_t) + X \]

define

\[ s = (p_1 + p_2)^2, \quad t = (p_1 - p_t)^2, \quad u = (p_2 - p_t)^2 \]

and \( s_4 = s + t + u - \sum m^2 \)

At partonic threshold \( s_4 \rightarrow 0 \)

Soft corrections

\[ \left[ \frac{\ln^k(s_4/m_t^2)}{s_4} \right]_+ \]

For the order \( \alpha_s^n \) corrections \( k \leq 2n - 1 \)

Resum these soft corrections for the double-differential cross section

At NNLL accuracy we need two-loop soft anomalous dimensions
Soft-gluon Resummation

moments of the partonic cross section with moment variable $N$:

$$\hat{\sigma}(N) = \int (d s_4 / s) \ e^{-N s_4 / s} \hat{\sigma}(s_4)$$

factorized expression for the cross section in $4 - \epsilon$ dimensions

$$\sigma^{f_1 f_2 \rightarrow tX} (N, \epsilon) = H_{IL}^{f_1 f_2 \rightarrow tX} (\alpha_s (\mu_R)) \ S_{LI}^{f_1 f_2 \rightarrow tX} \left( \frac{m_t}{N \mu_F}, \alpha_s (\mu_R) \right)$$

$$\times \prod J_{\text{in}} (N, \mu_F, \epsilon) \prod J_{\text{out}} (N, \mu_F, \epsilon)$$

$H_{IL}^{f_1 f_2 \rightarrow tX}$ is hard function and $S_{LI}^{f_1 f_2 \rightarrow tX}$ is soft function

$S_{LI}$ satisfies the renormalization group equation

$$\left( \mu \frac{\partial}{\partial \mu} + \beta(g_s) \frac{\partial}{\partial g_s} \right) S_{LI} = -(\Gamma_S^{\dagger})_{LK} S_{KI} - S_{LK} (\Gamma_S)_{KI}$$

Soft anomalous dimension $\Gamma_S$ controls the evolution of the soft function

which gives the exponentiation of logarithms of $N$
At one loop

\[ \Gamma_{S11}^{t(1)} = C_F \left[ \ln \left( \frac{t(t - m_t^2)}{m_t s^{3/2}} \right) - \frac{1}{2} \right] \]
\[ \Gamma_{S12}^{t(1)} = C_F \frac{C_F}{2N} \ln \left( \frac{u(u - m_t^2)}{s(s - m_t^2)} \right) \]
\[ \Gamma_{S21}^{t(1)} = \ln \left( \frac{u(u - m_t^2)}{s(s - m_t^2)} \right) - C_F \]

At two loops

\[ \Gamma_{S11}^{t(2)} = C_A \left( \frac{67}{36} - \frac{\zeta_2}{2} \right) - \frac{5}{18} n_f \Gamma_{S11}^{t(1)} + C_F C_A \frac{(1 - \zeta_3)}{4} \]
\textit{t-channel production at aNNLO}

Single-top $t$-channel aNNLO cross sections $m_t = 172.5$ GeV

\begin{center}
\includegraphics[width=\textwidth]{plot.png}
\end{center}
Top $p_T$ distributions in $t$-channel production at the LHC

N. Kidonakis, CIPANP 2018, Palm Springs, CA, May 2018
Top $p_T$ distributions in $t$-channel production at the LHC

N. Kidonakis, CIPANP 2018, Palm Springs, CA, May 2018
s-channel production

At one loop

\[
\Gamma^s_{S\ 11} = C_F \left[ \ln \left( \frac{s - m_t^2}{m_t \sqrt{s}} \right) - \frac{1}{2} \right] \\
\Gamma^s_{S\ 12} = \frac{C_F}{2N} \ln \left( \frac{u(u - m_t^2)}{t(t - m_t^2)} \right) \\
\Gamma^s_{S\ 21} = \ln \left( \frac{u(u - m_t^2)}{t(t - m_t^2)} \right)
\]

\[
\Gamma^s_{S\ 22} = C_F \ln \left( \frac{s - m_t^2}{m_t \sqrt{s}} \right) - \frac{1}{N} \ln \left( \frac{u(u - m_t^2)}{t(t - m_t^2)} \right) + \frac{N}{2} \ln \left( \frac{u(u - m_t^2)}{s(s - m_t^2)} \right) - \frac{C_F}{2}
\]

At two loops

\[
\Gamma^s_{S\ 11} = CA \left[ \frac{67}{36} - \frac{\zeta_2}{2} \right] - \frac{5}{18} n_f \Gamma^s_{S\ 11} + C_F CA \frac{(1 - \zeta_3)}{4}
\]
s-channel production at aNNLO

Single-top s-channel aNNLO cross sections \( m_t = 172.5 \text{ GeV} \)
Associated $tW$ production

At one loop

$$\Gamma_{tW}^{(1)} = C_F \left[ \ln \left( \frac{m_t^2 - t}{m_t \sqrt{s}} \right) - \frac{1}{2} \right] + \frac{C_A}{2} \ln \left( \frac{m_t^2 - u}{m_t^2 - t} \right)$$

At two loops

$$\Gamma_{tW}^{(2)} = \left[ C_A \left( \frac{67}{36} - \frac{\zeta_2}{2} \right) - \frac{5}{18} n_f \right] \Gamma_{tW}^{(1)} + C_F C_A \frac{1 - \zeta_3}{4}$$
$tW$ production at $aN^3\text{LO}$

$tW^+ + \bar{t}W^+$ $aN^3\text{LO}$ cross section $\quad m_t=172.5$ GeV

\begin{tikzpicture}
\begin{axis}[
    scale only axis,
    width=\textwidth,
    height=10cm,
    axis x line=bottom,
    axis y line=left,
    xlabel=$S^{1/2}$ (TeV),
    ylabel=$\sigma$ (pb),
    xmin=6,
    xmax=14,
    ymin=10,
    ymax=100,
    legend entries={aN$^3\text{LO}$, ATLAS, CMS, ATLAS&CMS},
    legend style={at={(0.55,1)},anchor=north}
]
\addplot[black,thick,solid] coordinates {
(6,10)
(7,20)
(8,30)
(9,40)
(10,50)
(11,60)
(12,70)
(13,80)
(14,90)
};
\addplot[red,mark=*,thick] coordinates {
(7,20)
(13,80)
};
\addplot[blue,mark=square,thick] coordinates {
(8,30)
(13,80)
};
\addplot[black,mark=square,thick] coordinates {
(7,20)
(13,80)
};
\end{axis}
\end{tikzpicture}
Top quark $p_T$ and rapidity distributions in $tW$ production

Top $p_T$ distribution in $tW$ production at LHC $aN^3LO \ m_t=173.3$ GeV

Top rapidity distribution in $tW$ production at LHC $aN^3LO \ m_t=173.3$ GeV

N. Kidonakis, CIPANP 2018, Palm Springs, CA, May 2018
Normalized top quark distributions in $tW$ production

Normalized top $p_T$ distribution $tW$ aN$^3$LO

Normalized rapidity distribution
production via anomalous couplings

\[ \Delta \mathcal{L}^{\text{eff}} = \frac{1}{\Lambda} \kappa_{tqZ} e \bar{t} (i/2)(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu) q F_{Z \mu \nu} + \text{h.c.} \]

- \( g \ u \to t \ Z \) at LHC aNNLO \( k_{wZ}=0.01 \)

\[ \sigma \ (\text{fb}) \]

- 14 TeV
- 13 TeV
- 8 TeV
- 7 TeV

- K-factors aNNLO/NLO

\[ m_\tau \ (\text{GeV}) \]

- 165
- 170
- 175
- 180

N. Kidonakis, CIPANP 2018, Palm Springs, CA, May 2018
$tZ$ production via anomalous couplings

Top-quark $p_T$ and rapidity distributions

$$g\ u\rightarrow t\ Z\ \ \text{at LHC} \ \ aNNLO \ \ k_{uZ}=0.01$$

$$g\ c\rightarrow t\ Z\ \ \text{at LHC} \ \ aNNLO \ \ k_{cZ}=0.01$$

N. Kidonakis, CIPANP 2018, Palm Springs, CA, May 2018
Summary

- cross sections and distributions for single-top production
- soft-gluon corrections
- $t$-channel at aNNLO
- $s$-channel at aNNLO
- $tW$ production at aN$^3$LO
- excellent agreement with LHC and Tevatron data
- $tZ$ production via anomalous couplings
- high-order corrections are very significant