Precision top-quark physics

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Outline

- Introduction

- Top-quark pair production
  - NNLO and beyond
  - tt, Wt and bb4l

- ttH

- Summary

Many more interesting results presented in the Top Physics session
Introduction

The top quark has a very special place in the Standard Model

- It is the heaviest elementary particle $m_t \sim 173 \text{GeV}$  \( y_t \sim 1 \)

- It couples strongly to the Higgs boson $m_t = y_t v / \sqrt{2} \sim 173 \text{GeV}$

- It decays through EW interaction before hadronizing

  - $\tau_{\text{had}} \sim 1 / \Lambda_{\text{QCD}} \sim 10^{-23} \text{s}$
  
  - $\tau_t = 1 / \Gamma_t \sim \left( G_F m_t^3 |V_{tb}|^2 \right)^{-1} \sim 5 \cdot 10^{-25} \text{s}$

![Diagram of top quark decay]
Introduction

- Possible window on new physics

\[ \mathcal{A}_{tV} \sim \frac{y_t^2}{8\pi^2} \Lambda_{UV}^2 \]

- Events with top quarks provide an ubiquitous background to SM, Higgs measurements and new physics searches
**Introduction**

Main source of top-quark events at hadron colliders is $t\bar{t}$ production.

About 15 $t\bar{t}$ events per second at the LHC!

*gg contribution dominant at the LHC (85% at LO)*
Theoretical status

Inclusive cross section known at NNLO+NNLL in QCD

Bärnreuther, Czakon, Mitov (2012)
Czakon, Mitov (2012)
Czakon, Fiedler, Mitov (2013)
Czakon, Fiedler, Heymes, Mitov (2015,2016)

NNLO calculation independently* completed by our group

*The only common ingredient are the two-loop $gg$ and $q\bar{q}$ virtual amplitudes

Bärnreuther et al (2013)

For the $q\bar{q}$ channel recently confirmed by fully analytical calculation

Mastrolia et al (2022)

Excellent agreement with Top++!

\[
\begin{array}{|c|c|c|}
\hline
\sigma_{\text{NNLO}} \, [\text{pb}] & \text{MATRIX} & \text{TOP++} \\
\hline
8 \, \text{TeV} & 238.5(2)^{+3.9\%}_{-6.3\%} & 238.6^{+4.0\%}_{-6.3\%} \\
13 \, \text{TeV} & 794.0(8)^{+3.5\%}_{-5.7\%} & 794.0^{+3.5\%}_{-5.7\%} \\
100 \, \text{TeV} & 35215(74)^{+2.8\%}_{-4.7\%} & 35216^{+2.9\%}_{-4.8\%} \\
\hline
\end{array}
\]
MATRIX allows the user to evaluate fully differential cross sections for a wide class of processes at hadron colliders in NNLO QCD, NLO EW and NLO QCD for the loop-induced contribution. 

Publicly available here http://matrix.hepforge.org
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MATRIXv2.1

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Publicly available here

http://matrix.hepforge.org

Version 2.1 includes top-pair production.
NNLO corrections significantly improve the agreement with the data
NEW: PDF uncertainties: MATRIX+PineAPPL interface

Devoto, Jezo, Kallweit, Schwan (in preparation)

$pp \rightarrow t\bar{t}$ @ 13 TeV, $\mu_0 = H_T/2$

- PDF uncertainty
  - $m_{tt}$ vs. $p_T^{t_{\text{had}}}$

Plots: courtesy S. Devoto
Beyond NNLO effects

Further effects that can/should be included are EW corrections and soft-gluon resummations at small and large invariant masses

Relatively small impact but slightly improves the agreement with the data

Still threshold region not properly described

Resummation of Coulomb effects partially improves the situation
NNLOPS

Event generators keeping formal NNLO accuracy for inclusive observables

Recently achieved for $t\bar{t}$ with the MiNNLOPS method

Exploit available knowledge of transverse-momentum resummation

NNLO matching for colourless production well established

$t\bar{t}$ production first example of coloured final state with non trivial soft-radiation pattern

Allows to directly deploy NNLO precision into $t\bar{t}$ experimental analyses
Excellent agreement with NNLO prediction, with differences only at the permille level

Excellent description of the data

Implements where fixed order NNLO has problems (like $p_T$ of softer top quark)
NNLOPS

Top decay and spin correlations included at LO only

Still good description of the data
Top decay

- Narrow width approximation (NWA)
  - based on the limit \( \Gamma_t/m_t \to 0 \)
  - considerable simplifications from the factorisation of production and decay
  - treatment of spin-correlations possible

- Off-shell calculations
  - consider the complete process, say \( pp \to b\bar{b}l\bar{l}l + X \)
  - challenges come from high-multiplicity phase space and interferences between production and decay

Melnikov, Schulze (2009)

More on on-shell effects in the talk by Giovanni Pelliccioli
Full NNLO in NWA

NNLO predictions describe the $\Delta \phi(\ell \bar{\ell})$ well in the fiducial region while some tension exists when the comparison is done in the inclusive phase space.

Effect of extrapolation relevant at this level of precision.
Excellent description of the data both in shape and normalisation
Full NNLO in NWA

Reconstructed top $p_T$ normalised to $m_{t\bar{t}}$: extrapolated vs fiducial
Full NLO QCD and EW calculations

- Off-shell effects through complete process $pp \to b\bar{b}l\nu l\nu + X$ in NLO QCD
  - Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek (2010)
  - Denner, Dittmaier, Kallweit, Pozzorini (2012)
  - Heinrich et al (2013)

- Unified $t\bar{t}$ and $Wt$ with massive $b$-quarks
  - Cascioli, Kallweit, Maierhöfer, Pozzorini (2013)
  - Frederix (2013)

- NLO EW corrections to full $b\bar{b}l\nu l\nu$
  - Denner and Pellen (2016)
Finite-width effects of the top quark are typically small but more important than those of the W
Isolating $W_t$

NLO $W_t$ simulations typically based on either

- **Diagram Removal (DR):** removing doubly resonant diagrams

- **Diagram Subtraction (DS):** cancelling doubly resonant contributions in a gauge invariant way

These methods are a significant source of uncertainty for many BSM searches
Unified $tt$ and $Wt$ description

Experimental studies have shown the limitations of simulations based on subtraction of $Wt$ contribution.

$$m_{bl}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

Low $m_{bl}^{\text{minimax}}$ region dominated by doubly resonant topologies.

High $m_{bl}^{\text{minimax}}$ region properly modelled by full $tt+Wt$ simulation.

Full $tt+Wt$ prediction  Jezo, Lindert, Nason, Oleari, Pozzorini (2016)
Required two-loop amplitudes are beyond current possibilities

Fully validated at NLO
The associated production of the Higgs boson with a top-quark pair is a crucial process at the LHC.

It allows a direct extraction of the top Yukawa.

Experimental uncertainties are now at the $\mathcal{O}(20\%)$ level but expected to go down to the $2\%$ level at the end of the HL-LHC.

Current predictions based on NLO QCD+EW (+ resummations) affected by $\mathcal{O}(10\%)$ uncertainty.

Missing ingredients for NNLO are the two-loop $gg \to t\bar{t}H$ and $q\bar{q} \to t\bar{t}H$ amplitudes.
**The idea:** use an approximation for the missing two-loop amplitude (similar in spirit to recent $2 \rightarrow 3$ NNLO calculations where leading colour approximation for the 2-loop is used)

\[ \mathcal{M}(\{p_i\}, k) \simeq F(\alpha_s(\mu_R); m/\mu_R) J(k) \mathcal{M}(\{p_i\}) \]

Soft limit of the scalar heavy-quark form factor

Approximated term has very small impact

<table>
<thead>
<tr>
<th>$\sigma$ [pb]</th>
<th>$\sqrt{s} = 13$ TeV</th>
<th>$\sqrt{s} = 100$ TeV</th>
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</thead>
<tbody>
<tr>
<td>$\sigma_{LO}$</td>
<td>$0.3910^{+31.3%}_{-22.2%}$</td>
<td>$25.38^{+21.1%}_{-16.0%}$</td>
</tr>
<tr>
<td>$\sigma_{NLO}$</td>
<td>$0.4875^{+5.6%}_{-9.1%}$</td>
<td>$36.43^{+9.4%}_{-8.7%}$</td>
</tr>
<tr>
<td>$\sigma_{NNLO}$</td>
<td>$0.5070 (31)^{+0.9%}_{-3.0%}$</td>
<td>$37.20 (25)^{+0.1%}_{-2.2%}$</td>
</tr>
</tbody>
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NNLO effect is about $+4\%$ at 13 TeV and $+2\%$ at 100 TeV

Catani, Devoto, Mazzitelli, Kallweit, Savoini, MG (2022)
Summary

- Top quarks are ubiquitous at the LHC

- Precise control of top production is fundamental to tame backgrounds in most of BSM searches and to fully exploit the LHC potential

- Theoretical predictions in good shape with NNLO+NLO EW becoming the standard

- NNLO precision starts to be deployed in MC generators

- Further progress is expected/needed to include off-shell effects beyond NLO

- First NNLO results for ttH