NLO QCD corrections for off-shell $t\bar{t}b\bar{b}$

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Based on arXiv:2105.08404

RADCOR-LoopFest 2021
FSU, Tallahassee, FL, USA, 19 May 2021
The Higgs boson and the top-Yukawa coupling

2012: discovery of the Higgs boson at the LHC $\Rightarrow$ tests on the Higgs sector.

The top-Yukawa coupling $Y_t$

Direct probing: $pp \to t\bar{t}H$ (1% to the total $pp \to H$).

The dominant decay channel of the Higgs boson is

$$H \to b\bar{b}, \quad (BR = 58\%).$$

Therefore $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ is a prime ingredient to extract information on $Y_t$.
Features of the background

This channel is very challenging because of the so-called "Combinatorial background" → smearing of the Higgs boson peak in bottom-pair invariant mass.

Combinatorial background

- Actual signal: \( pp \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b} \rightarrow W^+W^- b\bar{b}b\bar{b} \)
- Irreducible background: \( pp \rightarrow t\bar{t}b\bar{b} \rightarrow W^+W^- b\bar{b}b\bar{b} \)
- Reducible background: \( pp \rightarrow t\bar{t}jj \rightarrow W^+W^- b\bar{b}jj \)

\[ \text{Bevilacqua, Worek '14} \]
**t\bar{t}b\bar{b} state of the art**

- **NLO QCD calculations with stable top quarks**: general idea about the size of the NLO corrections. Cannot provide reliable description of the top quark decay products and the radiation pattern.
  
  *Bredenstein, Denner, Dittmaier, Pozzorini '08, '09, '10 / Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09 / Worek '12 / Bevilacqua, Worek '14*

- **t\bar{t}b\bar{b}j NLO QCD** as an estimate of beyond NLO corrections.
  
  *Buccioni, Kallweit, Pozzorini, Zoller '19*

- **NLO QCD matched to parton shower (NLO+PS)**: information on the radiation pattern. Top quark decays omitted or performed in the PS (no spin correlations).
  
  *Kardos, Trócsányi '14 / Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert '14 / Garzelli, Kardos, Trócsányi '15 / Bevilacqua, Garzelli, Kardos '17*

  LO spin correlated top quark decays.

  *Ježo, Lindert, Moretti, Pozzorini '18*

- **NLO QCD in the di-lepton top quark decay channel**: both production and decays without approximations. All off-shell and interference effects are taken into account.
  
  *Denner, Lang, Pellen '20*
Characterization of the $t\bar{t}b\bar{b}$ background

Setup:
full off-shell
NLO-QCD corrections

Summary &
Outlook

$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$

HELAC-NLO

Results at the integrated level

Initial state $b$-quark contributions

Size of corrections

Theoretical uncertainties

Comparisons

Are they negligible?

$b$-jet tagging schemes

Differential distributions

Size of corrections

Theoretical uncertainties

$bb$ distributions
Setup of the calculation

NLO QCD corrections to $pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu\bar{b}\bar{b}\bar{b}\bar{b}$ with full off-shell effects for LHC $\sqrt{s} = 13$ TeV. The 5 flavour scheme is employed.

Full off-shell effects

- Off-shell top quarks are described by Breit-Wigner propagators
- Double-, single- and non-resonant top quark contributions are included
- All interference effects consistently incorporated at the matrix element level

Cuts

$p_T(\ell) > 20$ GeV, $|y(\ell)| < 2.5$, $p_T(b) > 25$ GeV, $|y(b)| < 2.5$.

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21
Setup of the calculation

**HELAC-NLO**

- Theoretical predictions are stored in the form of modified *Les Houches Files* (*Alwall et al. '07*) and *ROOT Ntuples* (*Antcheva et al. '09, Bern et al. '14*).
- Kinematical cuts can be changed.
- New observables can be defined.
- Renormalization and factorization scales can be changed, as well as the PDF sets.

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Michele Lupattelli (RWTH Aachen)  
NLO QCD $t\bar{t}b\bar{b}$  
19/05/2021 7/20
A complex calculation

<table>
<thead>
<tr>
<th>One-loop correction type</th>
<th>Number of Feynman diagrams</th>
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<td>Vertex</td>
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<td>Box-type</td>
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<td>Heptagon-type</td>
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<td>Octagon-type</td>
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<td><strong>Total number</strong></td>
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<table>
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<th>Partonic Subprocess</th>
<th>Number of Feynman diagrams</th>
<th>Number of CS Dipoles</th>
<th>Number of NS Subtractions</th>
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<tbody>
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<tr>
<td>$q\bar{q} \rightarrow e^+\nu_e \mu^-\bar{\nu}_\mu \bar{b}b \bar{b}g$</td>
<td>9576</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>$gg \rightarrow e^+\nu_e \mu^-\bar{\nu}_\mu \bar{b}b \bar{b}q$</td>
<td>9576</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>$g\bar{q} \rightarrow e^+\nu_e \mu^-\bar{\nu}_\mu \bar{b}b \bar{b} \bar{q}$</td>
<td>9576</td>
<td>50</td>
<td>10</td>
</tr>
</tbody>
</table>

*Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21*
Integrated fiducial cross section

The process receives large NLO QCD corrections (89%) and significant reduction of the theoretical error going from LO to NLO.

*Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21*

**Fixed scale**

\[ \mu_R = \mu_F = \mu_0 = m_t \text{ and } \text{NNPDF3.1} \]

\[ \sigma^\text{LO} = 6.998^{+4.525(65\%)}_{-2.569(37\%)} \text{ fb} \]

\[ \sigma^\text{NLO} = 13.24^{+2.33(18\%)}_{-2.89(22\%)} \text{ fb} \]

**Dynamical scale**

\[ H_T = p_T(b_1) + p_T(b_2) + p_T(b_3) + p_T(b_4) + p_T(e^+) + p_T(\mu^-) + p_T^{\text{miss}} \]

\[ \mu_R = \mu_F = \mu_0 = H_T/3 \text{ and } \text{NNPDF3.1} \]

\[ \sigma^\text{LO} = 6.813^{+4.338(64\%)}_{-2.481(36\%)} \text{ fb} \]

\[ \sigma^\text{NLO} = 13.22^{+2.66(20\%)}_{-2.95(22\%)} \text{ fb} \]
Comparison with previous results

\[ \mu_0 = \mu_{DLP} = \frac{1}{2} \left[ \left( p_T^{\text{miss}} + \sum_{i=e^+, \mu^-, b_1, b_2, b_3, b_4, j} E_T(i) \right) + 2m_t \right]^{1/2} \left( \sum_{i=b_1, b_2, b_3, b_4, j} E_T(i) \right)^{1/2} \]

LO Results

\[ \sigma^{\text{LO}}_{\text{HELAC-NLO}}(\text{NNPDF3.1}, \mu_0 = \mu_{DLP}) = 5.201(2) +60\% -35\% \text{ fb}. \]
\[ \sigma^{\text{LO}}_{\text{DLP}}(\text{NNPDF3.1}, \mu_0 = \mu_{DLP}) = 5.198(4) +60\% -35\% \text{ fb}. \]

NLO Results

\[ \sigma^{\text{NLO}}_{\text{HELAC-NLO}}(\text{NNPDF3.1}, \mu_0 = \mu_{DLP}) = 10.28(1) +18\% -21\% \text{ fb}, \]
\[ \sigma^{\text{NLO}}_{\text{DLP}}(\text{NNPDF3.1}, \mu_0 = \mu_{DLP}) = 10.28(8) +18\% -21\% \text{ fb}. \]

Denner, Lang, Pellen '20 | Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21
**Comparison with ATLAS results**

**ATLAS cuts:**
\[
\begin{align*}
  p_T(\ell) & > 25 \text{ GeV}, \\
  |y(\ell)| & < 2.5, \\
  \Delta R(b\bar{b}) & > 0.4,
\end{align*}
\]

\[
\begin{align*}
  p_T(b) & > 25 \text{ GeV}, \\
  |y(b)| & < 2.5, \\
  \Delta R(\ell b) & > 0.4,
\end{align*}
\]

\[
\begin{align*}
  \sigma^{\text{ATLAS}}_{e\mu+4b} &= (25 \pm 6.5) \text{ fb} \\
  \sigma^{\text{HELAC-NLO}}_{e\mu+4b} &= (20.0 \pm 4.3) \text{ fb}
\end{align*}
\]

*ATLAS collaboration '18 | Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21*

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**Theoretical predictions**

<table>
<thead>
<tr>
<th>Theory</th>
<th>$\sigma_{e\mu+4b}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sherpa+OpenLoops (4FS)</td>
<td>17.2 ± 4.2</td>
</tr>
<tr>
<td>PowHEP-Box+Pythia 8 (4FS)</td>
<td>16.5</td>
</tr>
<tr>
<td>PowHEL+Pythia 8 (5FS)</td>
<td>18.7</td>
</tr>
<tr>
<td>PowHEL+Pythia 8 (4FS)</td>
<td>18.2</td>
</tr>
<tr>
<td>HELAC-NLO (5FS)</td>
<td>19.4 ± 4.2</td>
</tr>
</tbody>
</table>
Significant shape changes (corrections from 90% to 135%).

Scale dependence on the order of 20-30% (dominant contribution to the theoretical error).

PDF uncertainties small.
Differential distributions - fixed vs dynamical scale

$t\bar{t}b\bar{b}$ is a multi-scale process.

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- NLO QCD corrections [75%, 120%]
- Shape distortion of 45%

- NLO QCD corrections [-35%, 115%]
- Shape distortion of 150%
- Perturbative stability spoiled
NLO QCD corrections [85%, 120%] Left, [90%, 110%] Right
Smaller shape distortion for dimensionless angular distributions (35% Left, 20% Right)
Differential distributions - $M(bb)$

- NLO QCD corrections $[90\%, 150\%]$ Left, $[80\%, 110\%]$ Right
- Shape distortion 60% Left, 30% Right
Contribution of initial state $b$-quarks

Is it justified to neglect $b$-quark from the PDF?

We studied the impact of the sub-processes involving $b$ quarks in the initial state:

- **Born-like terms**: $b\bar{b}(, \ bb, \ \bar{b}\bar{b})$
- **Real-subtraction terms**: $b\bar{b}, \ bg, \ \bar{b}g(, \ bb, \ \bar{b}\bar{b})$

$b$-jet tagging schemes

- Charge **blind** tagging scheme
- Charge **aware** tagging scheme

We use the **anti-$k_t$** jet algorithm with $R = 0.4$. 
The charge blind tagging scheme is sensitive to the absolute flavour and does not attempt to tag the charge of the $b$-jet.

Experimental point of view

- **Advantage**: good $b$-jet tagging efficiency $\Rightarrow$ large event statistics.
- **Disadvantage**: cannot distinguish between $b$ and $\bar{b}$-jets.

Recombination rules

\[
\begin{aligned}
    b\bar{b} &\rightarrow g \\
    bb &\rightarrow g \\
    \bar{b}\bar{b} &\rightarrow g \\
    bg &\rightarrow b \\
    \bar{b}g &\rightarrow \bar{b}
\end{aligned}
\]
Charge aware tagging scheme

The charge aware tagging scheme is sensitive to the flavour and the charge of the $b$-jet.

**Experimental point of view**

- **Advantage:** can distinguish between $b$ and $\bar{b}$-jets.
- **Disadvantage:** might reduce $b$-jet tagging efficiency $\Rightarrow$ smaller event statistics.

**Recombination rules**

\[
\begin{align*}
    b\bar{b} & \rightarrow g, & bb & \rightarrow b, & \bar{b}\bar{b} & \rightarrow \bar{b} \\
    bg & \rightarrow b, & \bar{b}g & \rightarrow \bar{b}
\end{align*}
\]
Contribution of initial state $b$-quarks

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LO

The effects are of the order of 0.2%.

$$\sigma_{\text{LO no } b} = 6.813(3) \text{ fb}$$
$$\sigma_{\text{LO aware}} = 6.822(3) \text{ fb}$$
$$\sigma_{\text{LO blind}} = 6.828(3) \text{ fb}$$

NLO

The effects are of the order of 1%.

$$\sigma_{\text{NLO no } b} = 13.22(3) \text{ fb}$$
$$\sigma_{\text{NLO aware}} = 13.32(3) \text{ fb}$$
$$\sigma_{\text{NLO blind}} = 13.38(3) \text{ fb}$$
Summary & outlook

Summary

- LO and NLO predictions for $pp \rightarrow t\bar{t}b\bar{b}$:
  - full off-shell effects (di-lepton decay channel)
  - huge NLO QCD corrections $\sim 89\%$
  - theoretical uncertainties $\sim 20\%$

- agreement with experimental data (ATLAS)
- contributions of initial state $b$-quarks:
  - charge blind and charge aware tagging schemes
  - LO effects up to 0.2%, NLO effects up to 1%

Outlook

- on the size of the off-shell effects using the Narrow Width Approximation
- labelling of the $b$-jets using history reconstruction ($b$-jets from top decays vs prompt $b$-jets)