New NLOPS predictions for $b$-jet production in association with a top pair at the LHC

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In collaboration with:
*J. Lindert, N. Moretti and S. Pozzorini*
based on [arXiv:1802.00426]
Direct probe of top-quark Yukawa coupling

test of $m_t$ origin
Direct probe of top-quark Yukawa coupling

test of $m_t$ origin

Higgs BR + Total Uncert

$M_H$ [GeV]

$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$ $10^1$
$t\bar{t}H$ @ LHC run 2

- Direct probe of top-quark Yukawa coupling
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Significance 5.2σ
[arXiv:1804.02610]
- Direct probe of top-quark Yukawa coupling

<table>
<thead>
<tr>
<th>ATLAS Preliminary</th>
<th>$\sqrt{s}=13$ TeV, 13.2-13.3 fb$^{-1}$</th>
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<tbody>
<tr>
<td><strong>ttH(H→γγ)</strong> (13 TeV 13.3 fb$^{-1}$)</td>
<td>$-0.3$ +1.2$\pm$1.0</td>
</tr>
<tr>
<td>$\text{stat.}$</td>
<td>$-1.0$ $-1.0$</td>
</tr>
<tr>
<td>$\text{(tot.)}$</td>
<td>$-1.0$ $-1.2$</td>
</tr>
<tr>
<td>$\text{(stat., syst.)}$</td>
<td>$+0.2$ $-0.2$</td>
</tr>
<tr>
<td><strong>ttH(H→WW/ZZ)</strong> (13 TeV 13.2 fb$^{-1}$)</td>
<td>$2.5$ +1.3$\pm$1.1</td>
</tr>
<tr>
<td>$\text{stat.}$</td>
<td>$-1.1$ $-0.9$</td>
</tr>
<tr>
<td>$\text{(tot.)}$</td>
<td>$+0.7$ $+1.1$</td>
</tr>
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<td><strong>ttH combination (13 TeV)</strong></td>
<td>$1.8$ +0.7$\pm$0.7</td>
</tr>
<tr>
<td>$\text{stat.}$</td>
<td>$-0.7$ $-0.4$</td>
</tr>
<tr>
<td>$\text{(tot.)}$</td>
<td>$+0.4$ $+0.6$</td>
</tr>
<tr>
<td>$\text{(stat., syst.)}$</td>
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</tr>
<tr>
<td><strong>ttH combination (7-8 TeV, 4.5-20.3 fb$^{-1}$)</strong></td>
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</tr>
<tr>
<td>$\text{stat.}$</td>
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</tr>
</tbody>
</table>

| best fit $\mu_{ttH}$ for $m_H=125$ GeV |
|-------------------------|-----------------|
| 0                       | 2               |
| 4                       | 6               |
| 8                       | 10              |

**DIS 2018**
Direct probe of top-quark Yukawa coupling

Dominated by systematics!
• Direct probe of top-quark Yukawa coupling

\[ \text{CMS Preliminary} \]

\[ \begin{array}{ccc}
\text{Dilepton} & -0.04 & \mu \\
\text{Lepton+jets} & -0.43 & \text{tot. stat. syst.} \\
\text{Combined} & -0.19 & \text{stat. syst. stat. syst.} \\
\end{array} \]

Best fit \( \mu = \frac{\sigma}{\sigma_{\text{SM}}} \) at \( m_H = 125 \text{ GeV} \)

Dominated by systematics!
• Direct probe of top-quark Yukawa coupling
Large $t\bar{t} + b$-jets background and its theory uncertainties are bottleneck of $t\bar{t}H(b\bar{b})$ searches.

Modern tools support automated $t\bar{t}b\bar{b}$ simulations, but it remains highly nontrivial multi-particle multi-scale process.

Realistic estimates of theory uncertainties necessitate understanding of dynamics governing $pp \rightarrow t\bar{t}b\bar{b}$ as well as technical aspects related to:

- 5F/4F scheme choice
- NLO+PS matching
- PS effects
How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F
  - $t\bar{t}j$ tree MEs + $g \rightarrow b\bar{b}$ shower splittings

![Diagram 1](image)

$gg \rightarrow t\bar{t}g$ + FS splittings

$\bar{b}g \rightarrow t\bar{t}\bar{b}$ + IS splittings

- Formal accuracy: not even LO
- $t\bar{t}b\bar{b}$ MEs crucial for realistic theory uncertainty estimates
- However PS allows for accurate tuning to data
How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F ... **insufficient accuracy**

- Option 2: (N)LO merging $t\bar{t} + 0, 1, 2$ jets 5F
  - $t\bar{t} + 0, 1, 2$ jet MEs and $g \rightarrow b\bar{b}$ splittings

![Diagram showing softer and harder b-quarks](image)

- Precision and CPU cost strongly dependent on the merging cut $Q_{\text{cut}}$
- Does this describe $t\bar{t} + b$-jets mostly through $t\bar{t}b\bar{b}$ MEs though?
• $t\bar{t} + 0, 1, 2$ jet LO merging with $Q_{\text{cut}} = 20$ GeV

$$N_{b\text{jets}}$$

$N_{b\text{jets}}$ with $ttbb$ cuts

• Observables with $\geq 1$ additional $b$-jets
  ▶ dominated by $t\bar{t} + 2$jet MEs (suggesting ME precision)
Amount of $t\bar{t}+b$-jets ME information

- $t\bar{t} + 0,1,2$ jet LO merging with $Q_{\text{cut}} = 20$ GeV

- Observables with $\geq 1$ additional $b$-jets
  - actually dominated by MEs with 2 light jets and no $b$-jets (up to $Q \sim 100$ GeV)!
How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F ... insufficient accuracy

- Option 2: (N)LO merging $t\bar{t} + 0, 1, 2$ jets 5F
  - $t\bar{t} + 0, 1, 2$ jet MEs and $g \rightarrow b\bar{b}$ splittings
  - Precision and CPU cost strongly dependent on the merging cut $Q_{cut}$

- Does this describe $t\bar{t} + b$-jets mostly through $t\bar{t}b\bar{b}$ MEs though?

No!
How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F ... insufficient accuracy

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softer $b$-quarks

$\leftrightarrow$

$t\bar{t} + $ PS

$t\bar{t}j + $ PS

$t\bar{t}jj + $ PS

$\Rightarrow$

$t\bar{t}j$ + PS

$t\bar{t}jj$

$t\bar{t}bb$
How to simulate $t\bar{t} + b$-jets?

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- Option 3: $t\bar{t}b\bar{b}$ at NLO+PS

- NLO+PS precision for $t\bar{t} + 2b$-jet and $t\bar{t} + 1b$-jet observables
How to simulate $t\bar{t} + b$-jets?

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QCD production of $t\bar{t}b\bar{b}$

- Key features of 4F $pp \to t\bar{t}b\bar{b}$:
  - 6 ext. coloured particles, 34 LO diagrams, multiple scales $5 - 500$ GeV
  - Dominated by topologies with FS $g \to bb$ splittings

- At NLO QCD

  - 5FNS ($m_b = 0$): [Bredenstein et al. ’09–’10; Bevilacqua et al. ’10]
  - 4FNS ($m_b > 0$): [Cascioli et al. ’13]

- $\sigma_{t\bar{t}bb} \propto \alpha_s^4(\mu_R) \Rightarrow$ scale uncertainty:
  - $\sim 80\%$ @ LO
  - $20 - 30\%$ @ NLO
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QCD production of $t\bar{t}b\bar{b}$ @NLO+PS

- Available $t\bar{t}b\bar{b}$ calculations @NLO+PS in 2016:
  - Powhel [Garzelli et al. ’13/’14]
    - 5F scheme, POWHEG matching
    - requires a generation cut
  - Sherpa+OpenLoops [Cascioli et al. ’13]
    - 4F scheme, S-MC@NLO matching
  - MG5_aMC@NLO [Alwall et al. ’14]
    - 4F scheme, MC@NLO matching
    - no dedicated study
Tuned tool comparison in YR4

- YR4 [arXiv:1610.07922]:

  \[ M_{j_b1j_b2} \]

  - Sherpa+OpenLoops vs. PowHe1+PY8
    - Good agreement also in observables with large NLO+PS corrections

  - Sherpa+OpenLoops vs. MG5_aMC@NLO+PY8
    - Sizable differences in NLO radiation pattern
    - Strong resummation-scale sensitivity of \( t\bar{t}b\bar{b} + \text{jet} \) in MG5_aMC@NLO+PY8
Tuned tool comparison in YR4

- **YR4** [arXiv:1610.07922]:

  ![Graph 1](image1.png)

  - $M_{j_b f_{b2}}$

  ![Graph 2](image2.png)

  - $p_T^{j_{b1}}$

  “double-splittting”

- **Sherpa+OpenLoops vs. PowHel+PY8**
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    - Strong resummation-scale sensitivity of $t\bar{t}b\bar{b}$+jet in MG5_aMC@NLO+PY8
    - New: MG5_aMC@NLO+HW++ in good agreement with Sherpa+OpenLoops
Tuned tool comparison in YR4

- Sherpa+OpenLoops vs. MG5_aMC@NLO+PY8
  - Sizable differences in NLO radiation pattern
  - Considerable resummation-scale sensitivity in MG5_aMC@NLO+PY8
  - Strong shower dependence in MG5_aMC@NLO (PY8 vs HW++)

? 

Surprisingly large matching/shower uncertainty? Issue in either Sherpa or MG5_aMC@NLO?

- How about trying a different matching method?
  - POWHEG method has no resummation scale dependence
  - POWHEG-BOX+OpenLoops [TJ et al. ’18]
    - 4F scheme: $m_b > 0$ and no $b$ PDF
    - matrix elements from OpenLoops
  - Powhel [Bevilacqua et al. ’17]
    - 4F scheme: $m_b > 0$ and no $b$ PDF
    - matrix elements from HELAC
  - Comparison underway within the LHC HXSWG/ttH initiative
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Detailed comparison in [arXiv:1610.07922]

New!
QCD production of $t\bar{t}b\bar{b}$ @NLO+PS

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    - 4F scheme, POWHEG matching

MEs cannot describe quasi-collinear $g \rightarrow b\bar{b}$ splittings

MEs cover full $b$-quark phase space
Results in [arXiv:1802.00426]

- Perturbative uncertainties
  - Comparing “default NLOPS” vs. LOPS and fixed order (N)LO
  - Varying:
    - Factorization and renormalization scale
    - PDF variations
- Matching & shower uncertainties
  - Normalizing to “default NLOPS”
  - Varying:
    - Shower programs, i.e. Pythia 8.2 and Herwig 7.1
    - $g \to b\bar{b}$ modelling parameters
    - POWHEG matching parameters, $h_{damp}$ and $h_{bz}$
- Comparison against other $t\bar{t}b\bar{b}$ and $t\bar{t}$ generators
  - Comparing “default NLOPS” vs. $t\bar{t}$ NLOPS normalized to Sherpa
  - Including matching shower uncertainties
Results presented here

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Results in [arXiv:1802.00426]

- Predictions with stable top quarks
  - Perturbative uncertainties
  - Matching & shower uncertainties
  - Comparison against other $t\bar{t}b\bar{b}$ and $t\bar{t}$ generators

- Predictions with decayed top quarks in the dilepton channel
  - Study the impact of hadronization and MPI
  - Compare decays with and without spin correlations

- Setup identical to YR4 except for
  - Pythia: out of the box settings, no QED shower, no hadron decays, A14 tune
  - POWHEG-BOX: bornzerodamp applied also to final state $b$-quarks, $h_{bzd} = 2$
Results presented here

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  - Perturbative uncertainties
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Perturbative uncertainties

- fixed order NLO
- fixed order LO
- LO+PS matched with Pythia 8.2
- NLO+PS matched with Pythia 8.2, 7 point scale variations
- NLO+PS matched with Pythia 8.2, PDF variations
Perturbative uncertainties

- shapes of distributions stable with respect to NLO QCD corrections
- scale variations rather flat for inclusive observables
- PDF variations clearly subleading
- NLOPS corrections
  - ttb phase space: small
  - ttbb phase space: sizeable, i.e. ~ 27% in $M_{jb_1jb_2}$ above 100 GeV
Comparison with other generators

\[ N_{bj} \quad pT_{j1} \quad m_{b_1b_2} \]

LO+PS (Pythia 8.2), scalup, \( g \rightarrow b\bar{b} \) modelling variations
NLO+PS (Pythia 8.2), \( g \rightarrow b\bar{b} \) modelling variations

- Upper frame: POWHEG-BOX \( t\bar{t}b\bar{b} \) normalized to SHERPA \( t\bar{t}b\bar{b} \)
- Middle frame: POWHEG-BOX \( t\bar{t} \) normalized to SHERPA \( t\bar{t} \)
- Lower frame: POWHEG-BOX \( t\bar{t} \) normalized to \( t\bar{t}b\bar{b} \)
Comparison with other generators

- excellent agreement with SHERPA at NLOPS for both $t\bar{t}b\bar{b}$ and $t\bar{t}$
- drastic shower uncertainty reduction
  - from LOPS to NLOPS
  - from $t\bar{t}$ to $t\bar{t}b\bar{b}$
- $t\bar{t}$ does reasonably well, $t\bar{t}b\bar{b}$ mandatory for acceptable shower systematics
Comparison with other generators

\( N_{bj} \) \( p_{T_j} \) (ttb) \( m_{b_1b_2} \) (ttbb)

- excellent agreement with SHERPA at NLOPS for both \( t\bar{t}b\bar{b} \) and \( t\bar{t} \)
- drastic shower uncertainty reduction
  - from LOPS to NLOPS
  - from \( t\bar{t} \) to \( t\bar{t}b\bar{b} \)

\( tt \) (ttb) (ttbb)

\( t\bar{t} \) does reasonably well, \( t\bar{t}b\bar{b} \) mandatory for acceptable shower systematics.
Comparison with other generators

\[ N_{bj} \quad p_{Tj_1} \quad m_{b_1b_2} \] (ttb) (tt) (ttbb)

- excellent agreement with SHERPA at NLOPS for both \( t\bar{t}bb \) and \( t\bar{t} \)
- drastic shower uncertainty reduction
  - from LOPS to NLOPS
  - from \( t\bar{t} \) to \( t\bar{t}bb \)
- \( t\bar{t} \) does reasonably well, \( t\bar{t}bb \) mandatory for acceptable shower systematics
Summary and conclusions

- $t\bar{t}H$ searches suffer from poor accuracy of $t\bar{t} + b$-jet background simulations
  - $t\bar{t}b\bar{b}$ is very complex: large NLO(+PS) corrections, large shower uncertainties if $g \rightarrow b\bar{b}$ splitting left to the shower
  - Some theoretical predictions in slight tensions
- NLO+PS $t\bar{t}b\bar{b}$ simulations the sole alternative guaranteeing NLO accuracy for $t\bar{t} + b$-jet observables

NLOPS $t\bar{t}$ generators ameanable to a reasonable description of including $t\bar{t} + b$-jet observables, in principle. However, NLOPS $t\bar{t}b\bar{b}$ generators mandatory in order to achieve acceptable levess of shower systematics.

- NLO+PS $t\bar{t}b\bar{b}$ in POWHEG-BOX
  - show very good convergence
  - have shower uncertainties under control
  - agree extremely well with SHERPA
QCD production of $t\bar{t}b\bar{b}$

- Key features of 4F $pp \rightarrow t\bar{t}b\bar{b}$:
  - 6 external coloured partons, $\sigma_{t\bar{t}bb} \propto \alpha_s^4(\mu_R)$
  - 34 LO diagrams, multiple scales from 5 to 500 GeV
  - Dominated by topologies with FS $g \rightarrow bb$ splittings
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![Graphs showing production cross-section and differential distributions for $t\bar{t}b\bar{b}$ events.](image-url)
QCD production of $t\bar{t}b\bar{b}$

- Key features of 4F $pp \rightarrow t\bar{t}b\bar{b}$:
  - Dominated by topologies with $FS \ g \rightarrow bb$ splittings

$\sigma(N_{j_b})$

$M_{j_{b_1}j_{b_2}} (ttbb \ cuts)$

$M_{t\bar{t}} \times P \times P'$:

![Diagram showing the production process and matrix elements](image-url)
QCD production of $t\bar{t}b\bar{b}$

- Key features of 4F $pp \to t\bar{t}b\bar{b}$:
  - Dominated by topologies with FS $g \to bb$ splittings

![Graphs showing production cross-sections and mass distributions](image)

$M_{t\bar{t}} \times P \times P'$:
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- Key features of 4F $pp \to t\bar{t}b\bar{b}$:
  - Dominated by topologies with FS $g \to bb$ splittings
  - FS $g \to bb$ dominant, also away from collinear regime
  - IS $g \to b\bar{b}$ subdominant (no need for 5F resummation)

 supports choice of 4F scheme with $m_b > 0$ and no $b$-quark PDF
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Matching & shower uncertainties

NLO+PS matched with Pythia 8.2
NLO+PS matched with Herwig 7.1 (angular ordered)
LHE level (NLO + Sudakov suppressed harded emission)
LO+PS (Pythia 8.2), scalup ∈ \{H_T/4, H_T/2, H_T\}
LO+PS (Pythia8.2), weightGluonToQuark ∈ \{2, 4, 6, 8\}, renormMultFac ∈ \{0.1, 1, 10\}
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NLO+PS (Pythia8.2), h_damp ∈ \{H_T/4, H_T/2, H_T\}
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Matching & shower uncertainties

- effect of the parton shower
  - small in the ttb phase space, even for light-jet $p_T$
  - predictions with Pythia and Herwig in good agreement
- shower starting scale and $g \rightarrow b\bar{b}$
- hdamp and bornzerodamp
Matching & shower uncertainties

- effect of the parton shower
- shower starting scale and $g \rightarrow b\bar{b}$
  - jet bins with $N_b \geq 3, 4$ show sizable variations
  - light-jet spectrum depend strongly on scalup
- hdamp and bornzerodamp
Matching & shower uncertainties

- effect of the parton shower
- shower starting scale and $g \rightarrow b\bar{b}$
- **hdamp and bornzerodamp**
  - $h_{\text{damp}}$ dependence very small
  - $h_{\text{bzd}}$ dependence small, except for light-jet spectrum
Predictions with decayed top quarks

- **NLO+PS, spin corellated decays, hadronization off, MPI off**
- **NLO+PS, spin corellated decays, hadronization on, MPI off**
- **NLO+PS, spin corellated decays, hadronization on, MPI on**
- **NLO+PS, decays with Pythia 8.2, hadronization off, MPI off**

- decay has little impact on inclusive and production observables
- impact of hadronization and MPI limited to soft-regions
- spin corellation effects small but not negligible
MC@NLO vs Powheg matching (how to compare?)

**Splitting of radiation:** $S$-events (soft/singular) and $H$-events (hard/remnant)

$$d\sigma_S = d\Phi_B \bar{B}(\Phi_B) \left[ \Delta(t_{IR}) + \Delta(k_T) \frac{R_{soft}(\Phi_R)}{B(\Phi_B)} \Phi_{rad} \right]$$

$$d\sigma_H = d\Phi_R \left[ R(\Phi_R) - R_{soft}(\Phi_R) \right]$$

**Soft radiation integrated out in $\bar{B}$**  $\Rightarrow$  $\bar{B}/B = \text{local } K\text{-factor}$

$$\bar{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int d\Phi_{rad} R_{soft}(\Phi_B, \Phi_{rad})$$

**Powheg vs MC@NLO difference only in $R_{soft}$**

Powheg:  $R_{soft}(\Phi_R) = R(\Phi_R) g_{soft}(\Phi_{rad}, h_{damp})$

MC@NLO:  $R_{soft}(\Phi_R) = B(\Phi_B) \otimes K_{shower}(\Phi_{rad}) g_{soft}(\Phi_{rad}, \mu_Q)$

**Soft profile** $g_{soft}(\Phi_{rad}, \mu_Q)$

- restricts $R_{soft}$ below $\mu_Q$ (resummation scale), e.g. $\theta(\mu_Q^2 - k_T^2)$

$\Rightarrow$ **ideal choice for consistent comparison:** $h_{damp} = \mu_Q$ and same $g_{soft}$  

...?
Matching based on factorisation of $S$-radiation wrt hard $t\bar{t}b\bar{b}$ process

$$R_{\text{soft}}(\Phi_R) \simeq B(\Phi_B) \otimes K_{\text{soft/coll}}(\Phi_{\text{rad}}) \quad \text{for} \quad k_T < h_{\text{damp}} \sim m_t$$

What about radiation with $p_{T,b} < k_T < h_{\text{damp}}$? Soft or hard?

- $t\bar{t}b\bar{b}$ factorisation can fail and factorising hard $t\bar{t}$+jet subprocess can be more appropriate
- example: hard jet radiation in the direction of $b\bar{b}$ system
  - $\Phi_B \rightarrow \Phi_R$ FKS mappings $\Rightarrow$ $b\bar{b}$ system absorbs jet recoil and becomes much softer
  - $R(\Phi_R)$ enhancement that violates $ttbb$ factorisation
- similar issues expected also in MC@NLO matching

**Powheg “safety” system:** resummation only if $R_{\text{soft}} < h_{\text{bzd}} \times B \otimes K_{\text{soft/coll}}$

$$g_{\text{soft}}(\Phi_{\text{rad}}, h_{\text{damp}}, h_{\text{bzd}}) = \frac{h_{\text{damp}}^2}{h_{\text{damp}}^2 + k_T^2} \theta\left(h_{\text{bzd}}B(\Phi_B) \otimes K_{\text{soft/coll}}(\Phi_{\text{rad}}) - R(\Phi_R)\right)$$

$\Rightarrow$ high stability wrt $h_{\text{damp}}$ variations