

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

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In collaboration with:

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Based on [arXiv:2105.08404](https://arxiv.org/abs/2105.08404)

Annual meeting of the CRC TRR 257

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The Higgs boson and the top-Yukawa coupling

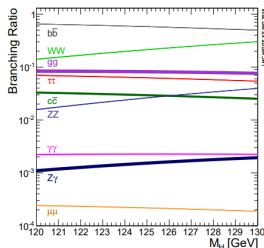
2012: discovery of the Higgs boson at the LHC $\Rightarrow$ tests on the Higgs sector.

The top-Yukawa coupling Y_t

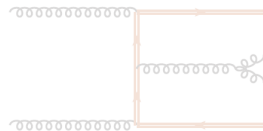
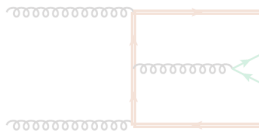
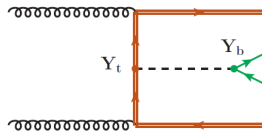
Direct probing: $pp \rightarrow t\bar{t}H$ (1% to the total $pp \rightarrow H$).
The dominant decay channel of the Higgs boson is

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

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



LHC Higgs Cross Section Working Group collaboration '16



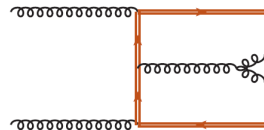
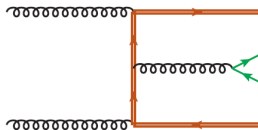
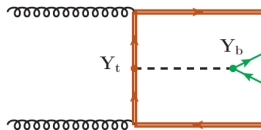
Bevilacqua, Worek '14

Features of the background

This channel is very challenging because of the so-called “**Combinatorial background**” $\rightarrow$ 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: $pp \rightarrow t\bar{t}jj \rightarrow W^+W^-b\bar{b}jj$



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).

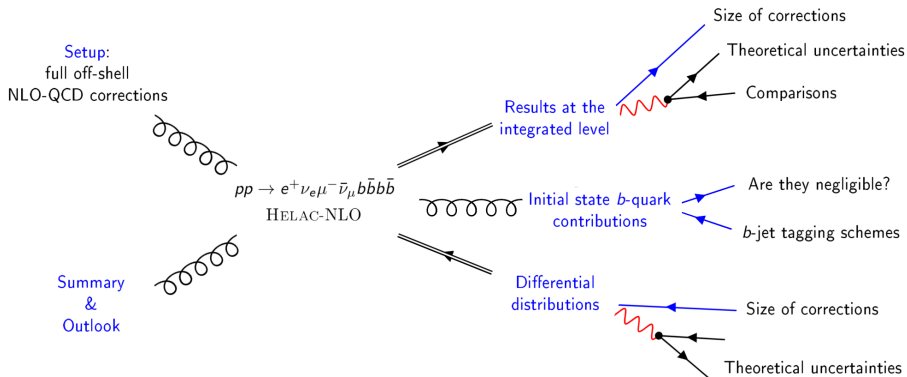
*Kardos, Trócsányi '14 | Cascioli, Maierhöfer, Moretti, Pozzorini, Siebert '14 |
Garzelli, Kardos, Trócsányi '15 | Bevilacqua, Garzelli, Kardos '17*

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



Setup of the calculation

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

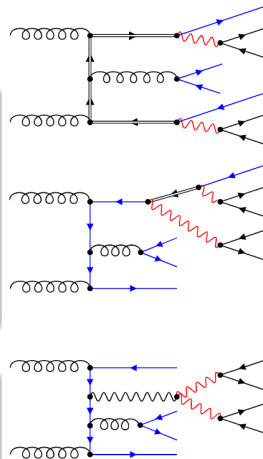
Cuts

$$p_T(\ell) > 20 \text{ GeV},$$

$$|y(\ell)| < 2.5,$$

$$p_T(b) > 25 \text{ GeV},$$

$$|y(b)| < 2.5,$$



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

$\mu_R = \mu_F = \mu_0 = m_t$ and NNPDF3.1

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

$$\sigma^{\text{NLO}} = 13.24^{+2.33(18\%)}_{-2.89(22\%)} [\text{scales}]^{+0.19(1\%)}_{-0.19(1\%)} [\text{PDF}] \text{ fb}$$

Dynamical scale

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

$\mu_R = \mu_F = \mu_0 = H_T/3$ and NNPDF3.1

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

$$\sigma^{\text{NLO}} = 13.22^{+2.66(20\%)}_{-2.95(22\%)} [\text{scales}]^{+0.19(1\%)}_{-0.19(1\%)} [\text{PDF}] \text{ fb}$$

Comparison with previous results

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

LO Results

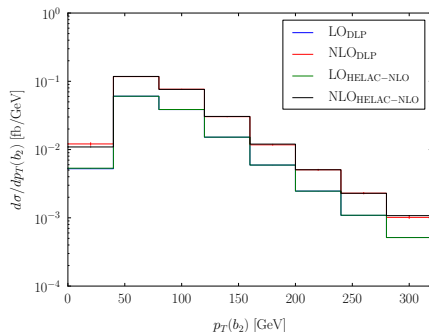
$$\sigma_{\text{HELAC-NLO}}^{\text{LO}}(\text{NNPDF3.1}, \mu_0 = \mu_{\text{DLP}}) = 5.201(2)^{+60\%}_{-35\%} \text{ fb.}$$

$$\sigma_{\text{DLP}}^{\text{LO}}(\text{NNPDF3.1}, \mu_0 = \mu_{\text{DLP}}) = 5.198(4)^{+60\%}_{-35\%} \text{ fb.}$$

NLO Results

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

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



Denner, Lang, Pellen '20 | Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21

Comparison with ATLAS results

ATLAS cuts:

$$p_T(\ell) > 25 \text{ GeV},$$

$$p_T(b) > 25 \text{ GeV},$$

$$|y(\ell)| < 2.5,$$

$$|y(b)| < 2.5,$$

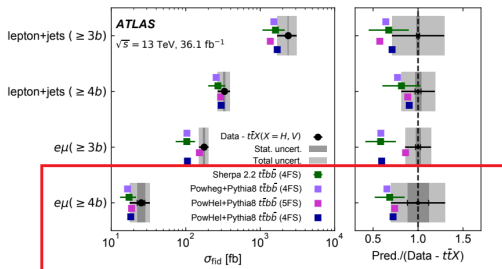
$$\Delta R(bb) > 0.4,$$

$$\Delta R(\ell b) > 0.4,$$

$$\sigma_{e\mu+4b}^{\text{ATLAS}} = (25 \pm 6.5) \text{ fb}$$

$$\sigma_{e\mu+4b}^{\text{HELAC-NLO}} = (20.0 \pm 4.3) \text{ fb}$$

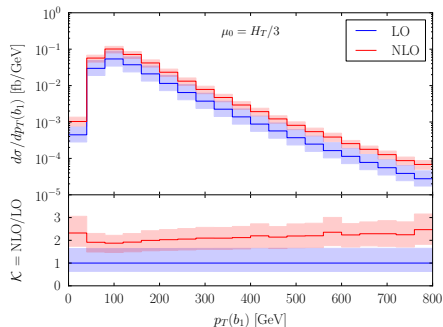
ATLAS collaboration '18 | Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21



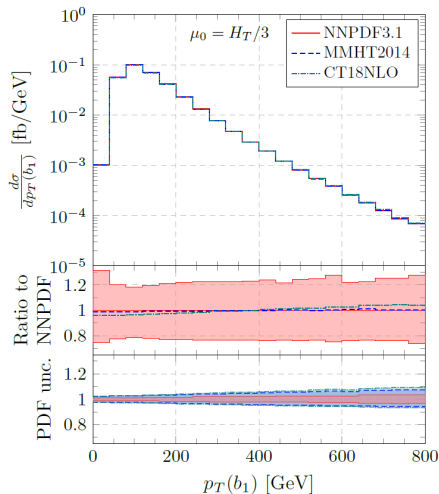
Theoretical predictions	$\sigma_{e\mu+4b} [\text{fb}]$
SHERPA+OPENLOOPS (4FS)	17.2 ± 4.2
POWHEG-BOX+PYTHIA 8 (4FS)	16.5
POWHEG+PYTHIA 8 (5FS)	18.7
POWHEG+PYTHIA 8 (4FS)	18.2
HELAC-NLO (5FS)	19.4 ± 4.2

Differential distributions - Uncertainties

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- 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**.

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 $R = 0.4$.

Charge blind tagging scheme

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 $\implies$ large event statistics.
- **Disadvantage:** cannot distinguish between b and $\bar{b}$ -jets.

Recombination rules

$$\begin{array}{ccc}
 b\bar{b} \rightarrow g & b\bar{b} \rightarrow g & b\bar{b} \rightarrow g \\
 bg \rightarrow b & \bar{b}g \rightarrow \bar{b} &
 \end{array}$$

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 $\implies$ smaller event statistics.

Recombination rules

$$\begin{array}{lll}
 b\bar{b} \rightarrow g & b\bar{b} \rightarrow b & b\bar{b} \rightarrow \bar{b} \\
 & b\bar{g} \rightarrow b & b\bar{g} \rightarrow \bar{b}
 \end{array}$$

Contribution of initial state b -quarks - Results

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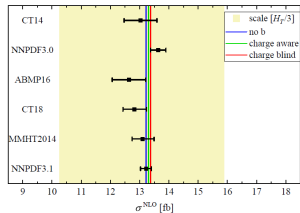
LO

The effects are of the order of 0.2%.

$$\sigma_{\text{no } b}^{\text{LO}} = 6.813(3) \text{ fb}$$

$$\sigma_{\text{aware}}^{\text{LO}} = 6.822(3) \text{ fb}$$

$$\sigma_{\text{blind}}^{\text{LO}} = 6.828(3) \text{ fb}$$



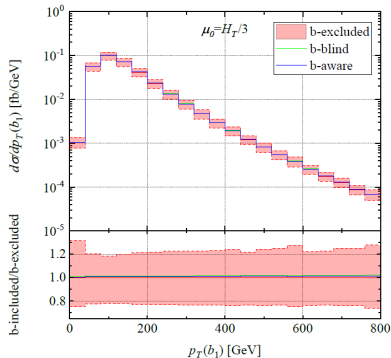
NLO

The effects are of the order of 1%.

$$\sigma_{\text{no } b}^{\text{NLO}} = 13.22(3) \text{ fb}$$

$$\sigma_{\text{aware}}^{\text{NLO}} = 13.31(3) \text{ fb}$$

$$\sigma_{\text{blind}}^{\text{NLO}} = 13.38(3) \text{ fb}$$



Summary & outlook

Summary

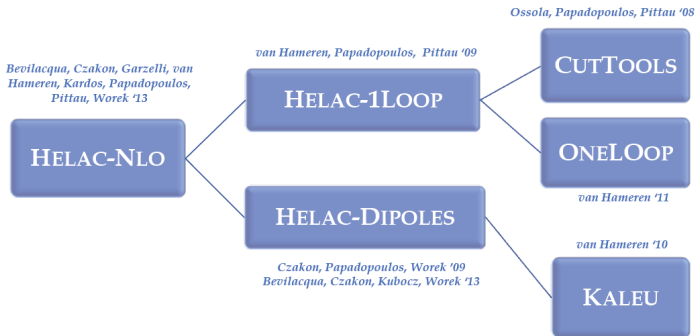
- LO and NLO predictions for $pp \rightarrow t\bar{t}b\bar{b}$:
 - full off-shell effects (di-lepton decay channel)
 - huge NLO QCD corrections $\sim 89\%$
 - theoretical uncertainties $\sim 20\%$
- agreement with experimental data (ATLAS)
- contributions of initial state b -quarks:
 - charge blind and 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)

BACKUP SLIDES

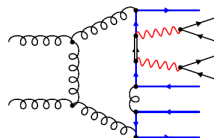
HELAC-NLO



- 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

A complex calculation

One-loop correction type	Number of Feynman diagrams
Self-energy	93452
Vertex	88164
Box-type	49000
Pentagon-type	25876
Hexagon-type	11372
Heptagon-type	3328
Octagon-type	336
Total number	271528



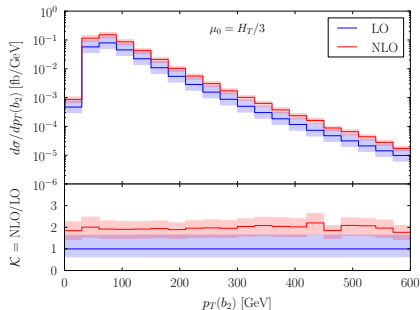
Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} g$	41364	90	18
$q\bar{q} \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} g$	9576	50	10
$gq \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} q$	9576	50	10
$g\bar{q} \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} \bar{q}$	9576	50	10

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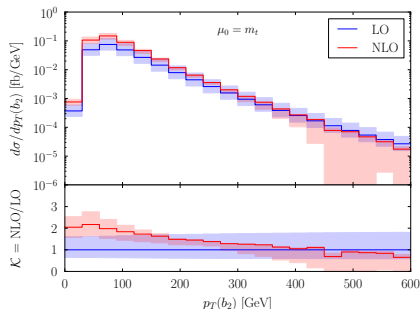
Differential distributions - fixed vs dynamical scale

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

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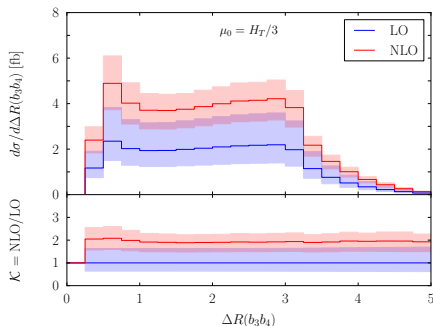
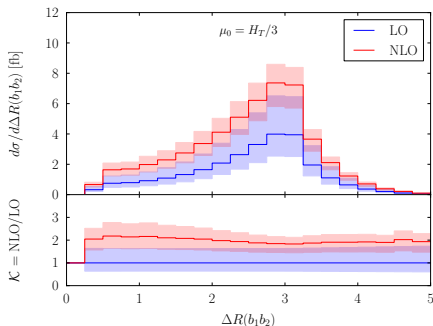
- NLO QCD corrections [75%, 120%]
- Shape distortion of 45%



- NLO QCD corrections [-35%, 115%]
- Shape distortion of 150%
- Perturbative stability spoiled

Differential distributions - $\Delta R(bb)$

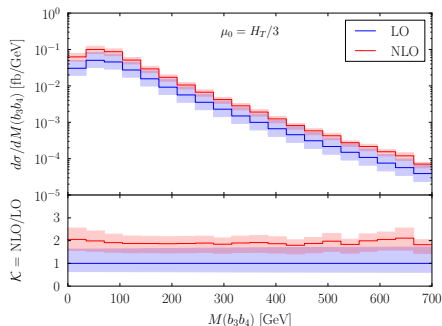
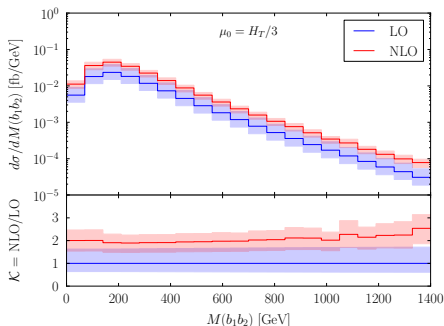
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- NLO QCD corrections [85%, 120%] Left, [90%, 110%] Right
- Smaller shape distortion for dimensionless angular distributions (35% Left, 20% Right)

Differential distributions - $M(bb)$

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- NLO QCD corrections [90%, 150%] Left, [80%, 110%] Right
- Shape distortion 60% Left, 30% Right