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

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The Higgs boson and the top-Yukawa coupling

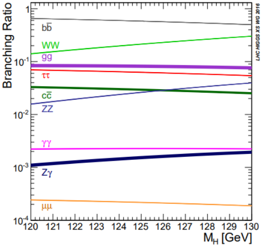
2012: discovery of the Higgs boson at the LHC $\Longrightarrow$ tests on the Higgs sector.

The top-Yukawa coupling Y_t

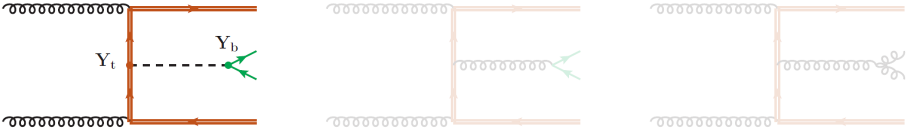
Direct probing: $pp \to t\bar{t}H$ (1% to the total $pp \to H$). The dominant decay channel of the Higgs boson is

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

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



LHC Higgs Cross Section Working Group collaboration '16



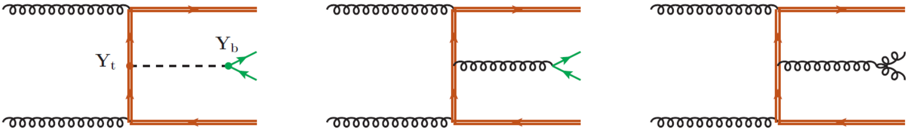
Bevilacqua, Worek '14

Features of the background

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

Combinatiorial background

- Actual signal: $pp \to t\bar{t}H \to t\bar{t}b\bar{b} \to W^+W^-b\bar{b}b\bar{b}$
- Irreducible background: $pp \to t\bar{t}b\bar{b} \to W^+W^-b\bar{b}b\bar{b}$
- Reducible background: $pp \to t\bar{t}jj \to W^+W^-b\bar{b}jj$



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$t\bar{t}b\bar{b}$ 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).

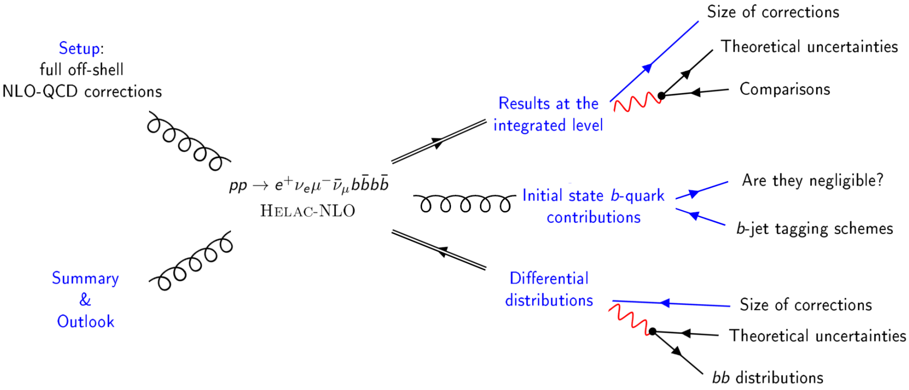
  Kardos, Trócsányi '14 | Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert '14 | Garzelli, Kardos, Trócsányi '15 | Bevilacqua, Garzelli, Kardos '17

  LO spin correlated top quark decays.

  Ježo, Lindert, Moretti, Pozzorini '18

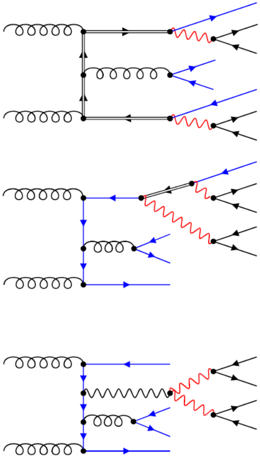
- NLO QCD in the di-lepton top quark decay channel: both production and decays without approximations. All off-shell and interference effects are taken into account.

  Denner, Lang, Pellen '20


Setup:
full off-shell
NLO-QCD corrections
Summary
&
Outlook
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$
HELAC-NLO
Results at the
integrated level
Size of corrections
Theoretical uncertainties
Comparisons
Initial state b-quark
contributions
Are they negligible?
b-jet tagging schemes
Differential
distributions
Size of corrections
Theoretical uncertainties
bb distributions

Setup of the calculation

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

$$p_T(\ell) > 20 \text{ GeV}\,, \qquad p_T(b) > 25 \text{ GeV}\,,$$

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

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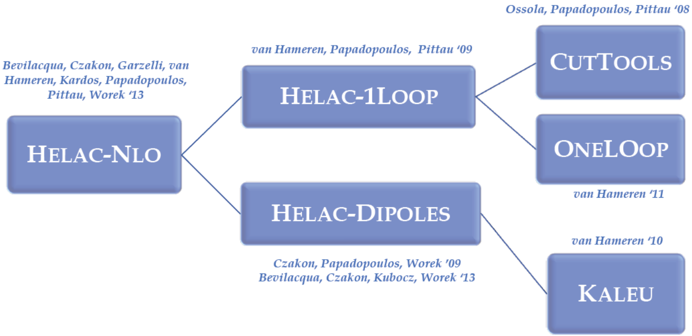
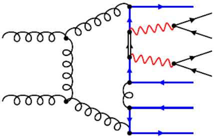
HELAC-NLO



- 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
$gg \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}\, b\bar{b}\, g$	41364	90	18
$q\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}\, b\bar{b}\, g$	9576	50	10
$gq \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}\, b\bar{b}\, q$	9576	50	10
$g\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}\, b\bar{b}\, \bar{q}$	9576	50	10

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Integrated fiducial cross section

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

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Fixed scale

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

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

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

Dynamical scale

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

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

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

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

Comparison with previous results

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

LO Results

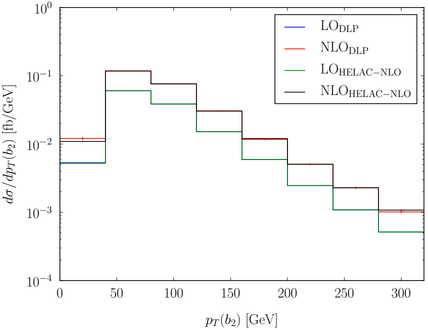
$$\sigma^{\rm LO}_{\rm HELAC-NLO}({\rm NNPDF3.1}, \mu_0 = \mu_{\rm DLP}) = 5.201(2)\,^{+60\%}_{-35\%}\,{\rm fb}\,.$$

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

NLO Results

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

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



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

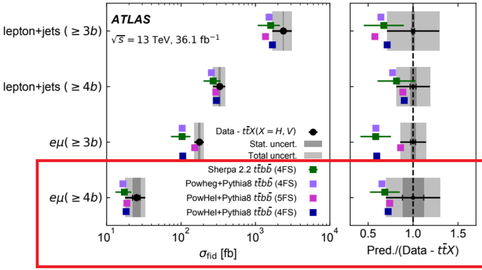
Comparison with ATLAS results

ATLAS cuts:

$$p_T(\ell) > 25 \text{ GeV}\,, \qquad p_T(b) > 25 \text{ GeV}\,,$$
$$|y(\ell)| < 2.5\,, \qquad |y(b)| < 2.5\,,$$
$$\Delta R(bb) > 0.4\,, \qquad \Delta R(\ell b) > 0.4\,,$$

$$\sigma^{\text{ATLAS}}_{e\mu+4b} = (25 \pm 6.5)\ \text{fb}$$
$$\sigma^{\text{HELAC-NLO}}_{e\mu+4b} = (20.0 \pm 4.3)\ \text{fb}$$

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



Theoretical predictions	$\sigma_{e\mu+4b}$ [fb]
Sherpa+OpenLoops (4FS)	17.2 ± 4.2
Powheg-Box+Pythia 8 (4FS)	16.5
PowHel+Pythia 8 (5FS)	18.7
PowHel+Pythia 8 (4FS)	18.2
Helac-NLO (5FS)	19.4 ± 4.2

Differential distributions - Uncertainties

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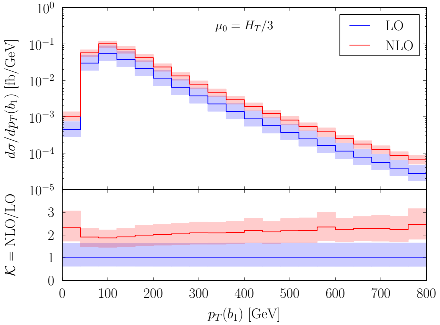

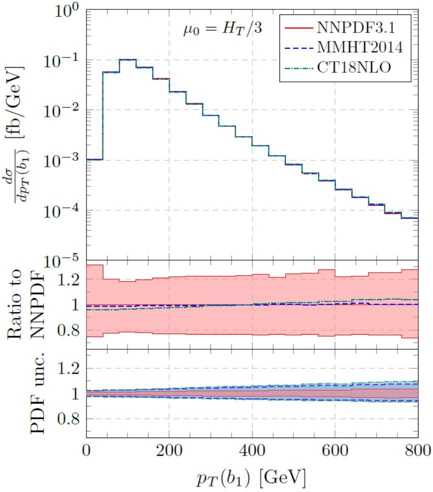

- Significant shape changes (corrections from 90% to 135%).
- Scale dependence on the order of 20-30% (dominant contribution to the theoretical error).

- PDF uncertainties small.

Differential distributions - fixed vs dynamical scale

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

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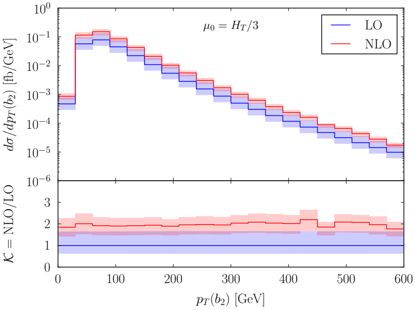

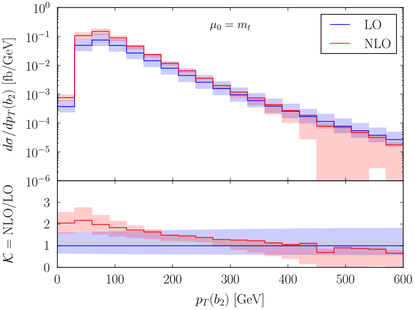

- NLO QCD corrections [75%, 120%]
- Shape distortion of 45%

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

Differential distributions - $\Delta R(bb)$

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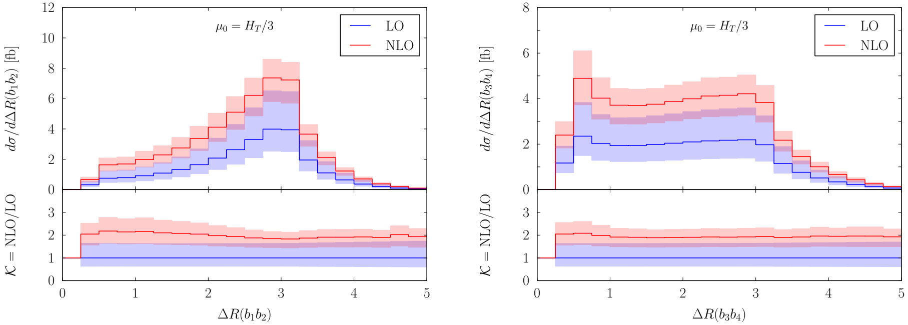

- NLO QCD corrections [85%, 120%] Left, [90%, 110%] Right
- Smaller shape distortion for dimensionless angular distributions (35% Left, 20% Right)

Differential distributions - $M(bb)$

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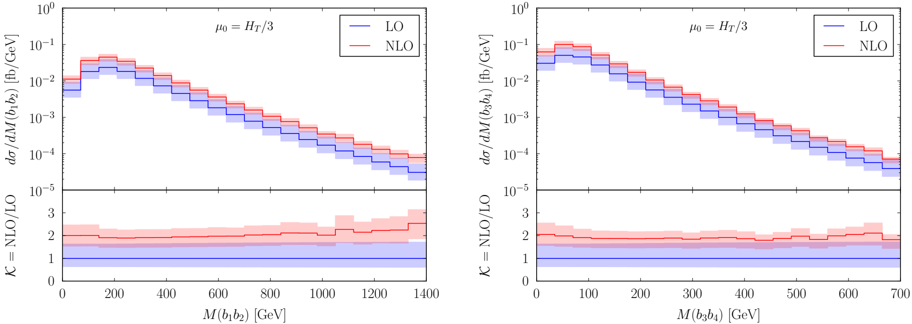

- NLO QCD corrections [90%, 150%] Left, [80%, 110%] Right
- Shape distortion 60% Left, 30% Right

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

Recombination rules

$$b\bar{b} \to g \qquad bb \to g \qquad \bar{b}\bar{b} \to g$$
$$bg \to b \qquad \bar{b}g \to \bar{b}$$

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 $\Longrightarrow$ smaller event statistics.

Recombination rules

$$b\bar{b} \to g \qquad bb \to b \qquad \bar{b}\bar{b} \to \bar{b}$$
$$bg \to b \qquad \bar{b}g \to \bar{b}$$

Contribution of initial state b-quarks - Results

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LO

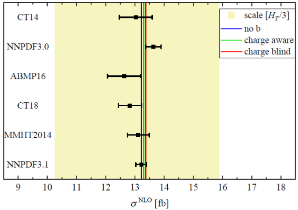
The effects are of the order of 0.2%.

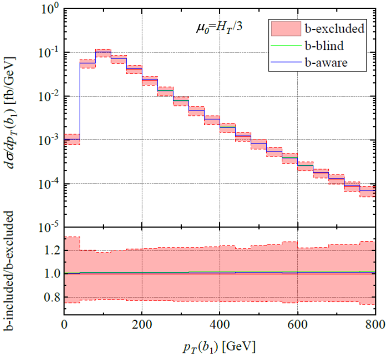
$$\sigma^{\mathrm{LO}}_{\mathrm{no\ b}} = 6.813(3)\ \mathrm{fb}$$
$$\sigma^{\mathrm{LO}}_{\mathrm{aware}} = 6.822(3)\ \mathrm{fb}$$
$$\sigma^{\mathrm{LO}}_{\mathrm{blind}} = 6.828(3)\ \mathrm{fb}$$

NLO

The effects are of the order of 1%.

$$\sigma^{\mathrm{NLO}}_{\mathrm{no\ b}} = 13.22(3)\ \mathrm{fb}$$
$$\sigma^{\mathrm{NLO}}_{\mathrm{aware}} = 13.31(3)\ \mathrm{fb}$$
$$\sigma^{\mathrm{NLO}}_{\mathrm{blind}} = 13.38(3)\ \mathrm{fb}$$





Summary & outlook

Summary

- LO and NLO predictions for $pp \to t\bar{t}b\bar{b}$:
  - 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)