off-shell $t\bar{t}b\bar{b}$ in the di-lepton channel

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14th International Workshop on Top Quark Physics
13 - 17 September 2021

Based on: JHEP 08 (2021) 008

Outline

Motivations for $t\bar{t}b\bar{b}$ at the LHC

- the need for more precision
- state of the art

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

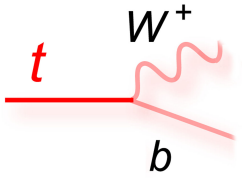
- Size of corrections
- Differential distributions
- Impact of b jet definitions

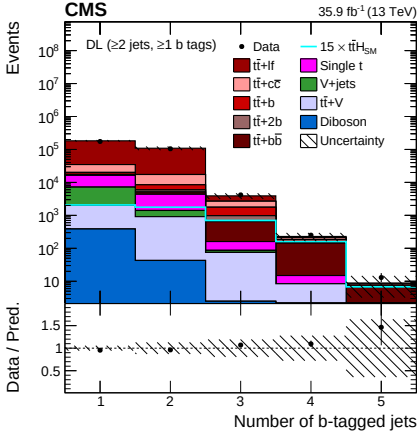
Summary & Outlook

Motivation

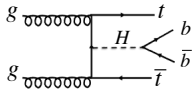
Motivation - Background

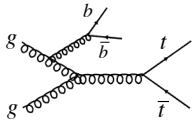
- Measurements of $pp \to t\bar{t}H$ with $H \to b\bar{b}$ are challenging!
- Large irreducible background due to $pp \to t\bar{t}b\bar{b}$
- Reducible background: $pp \to t\bar{t}jj$
- extra b jets from top decay: $t \to Wb$





$\Rightarrow t\bar{t}b\bar{b}$ main background for $N_{\text{b jets}} \geq 4$

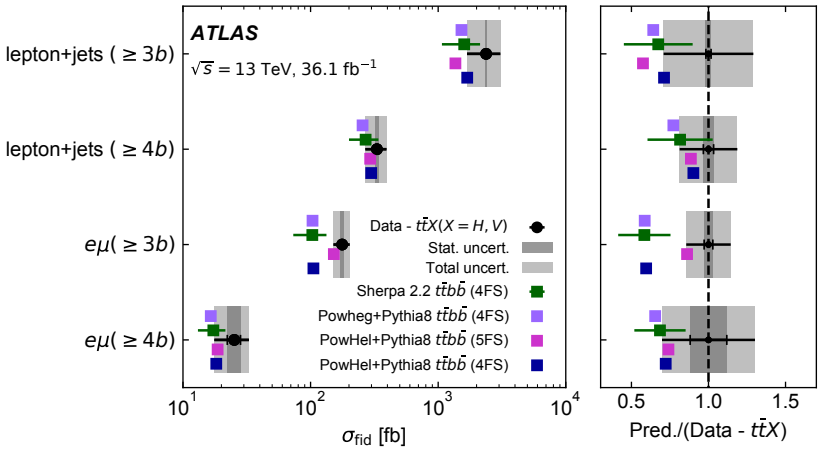




[CMS arXiv:1804.03682]

Motivation - Signal

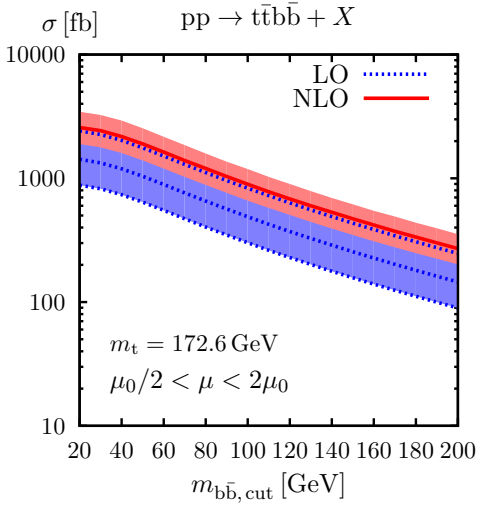
$pp \to t\bar{t}b\bar{b}$ measurement [ATLAS arXiv:1811.12113]

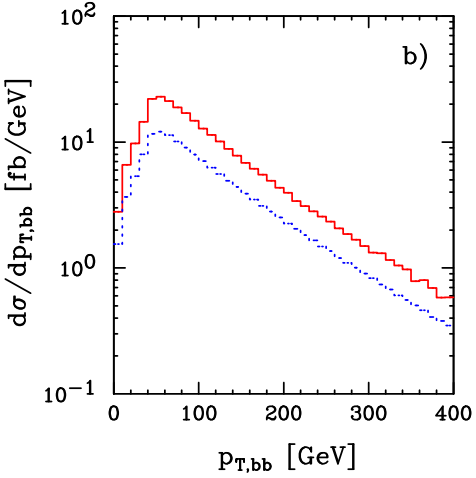


- Current predictions are systematically below data
- Can off-shell $t\bar{t}b\bar{b}$ model fiducial volumes better?

Motivation - Theory

[Bredenstein, Denner, Dittmaier, Pozzorini '09]





[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09]

- $t\bar{t}b\bar{b}$ is a true multi-scale process
- theoretically very challenging!

NLO QCD fixed order

$pp \to t\bar{t}b\bar{b}$ [Bredenstein, Denner, Dittmaier, Pozzorini '08,'09'10] [Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09] [Worek '12] [Bevilacqua, Worek '14]

$pp \to t\bar{t}b\bar{b}j$ [Buccioni, Kallweit, Pozzorini, Zoller '19]

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$ [Denner, Lang, Pellen '20] [Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

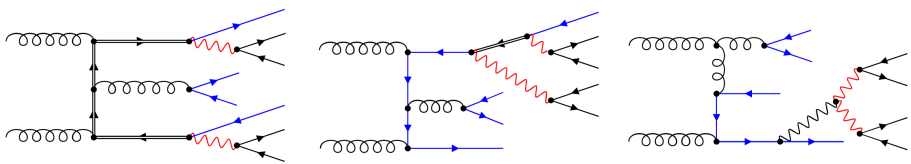
NLO + PS

- POWHEG matching [Kardos, Trócsányi '14] [Garzelli, Kardos, Trócsányi '15] [Bevilacqua, Garzelli, Kardos '17] [Ježo, Lindert, Moretti, Pozzorini '18]

- MC@NLO matching [Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert '14]

off-shell $t\bar{t}b\bar{b}$

NLO QCD corrections to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$ for LHC at $\sqrt{s} = 13$ TeV

- Full off-shell effects
  - 

    Double resonant Single resonant Non resonant
  - off-shell tops described by Breit-Wigner propagators
  - All interferences at the matrix element level

- Event selection:

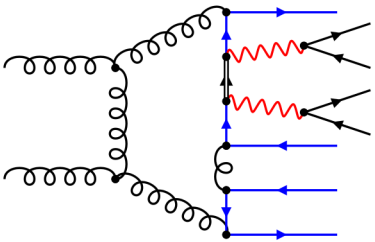
$$p_T(\ell) > 20\ \text{GeV}\,, \quad p_T(b) > 25\ \text{GeV}\,, \quad |y(\ell)| < 2.5\,, \quad |y(b)| < 2.5$$

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

A very complicated computation

A quick glimpse at the complexity of $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$

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

$\Rightarrow$ Computation performed with HELAC-NLO

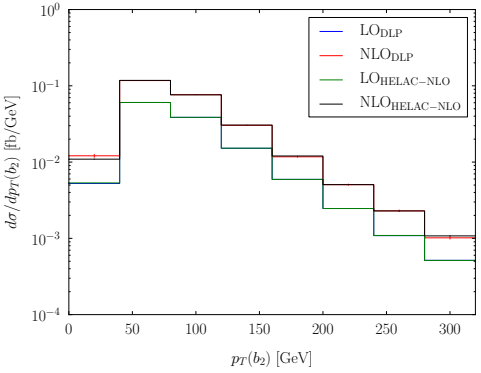
Comparison with literature

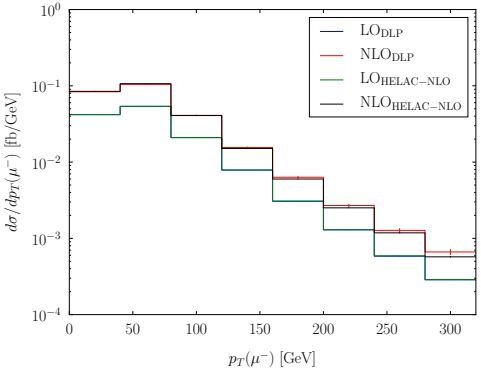
Comparison with results from Denner, Lang, Pellen '20

Integrated cross section

$$\sigma^{\text{NLO}}_{\text{HELAC}} = 10.28(1)^{+18\%}_{-21\%}\ \text{fb} \qquad \sigma^{\text{NLO}}_{\text{DLP}} = 10.28(8)^{+18\%}_{-21\%}\ \text{fb}$$

Differential distributions





Excellent agreement!

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

Integrated fiducial cross sections

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$ @ LHC_{13TeV}

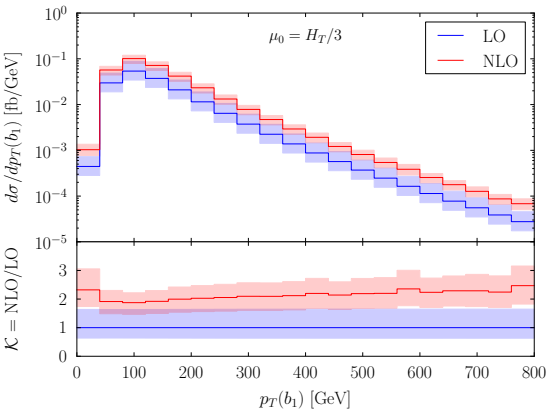
$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
$\mu_R = \mu_F = \mu_0 = m_t$						
25	6.998	$^{+4.525\ (65\%)}_{-2.569\ (37\%)}$	13.24	$^{+2.33\ (18\%)}_{-2.89\ (22\%)}$	$^{+0.19\ (1\%)}_{-0.19\ (1\%)}$	1.89
30	5.113	$^{+3.343\ (65\%)}_{-1.889\ (37\%)}$	9.25	$^{+1.32\ (14\%)}_{-1.93\ (21\%)}$	$^{+0.14\,(2\%)}_{-0.14\,(2\%)}$	1.81
35	3.775	$^{+2.498\ (66\%)}_{-1.401\ (37\%)}$	6.57	$^{+0.79\ (12\%)}_{-1.32\ (20\%)}$	$^{+0.10\,(2\%)}_{-0.10\,(2\%)}$	1.74
40	2.805	$^{+1.867\ (67\%)}_{-1.051\ (37\%)}$	4.70	$^{+0.46\ (10\%)}_{-0.91\ (19\%)}$	$^{+0.08\,(2\%)}_{-0.08\,(2\%)}$	1.68
$\mu_R = \mu_F = \mu_0 = H_T/3$						
25	6.813	$^{+4.338\ (64\%)}_{-2.481\ (36\%)}$	13.22	$^{+2.66\ (20\%)}_{-2.95\ (22\%)}$	$^{+0.19\ (1\%)}_{-0.19\ (1\%)}$	1.94
30	4.809	$^{+3.062\ (64\%)}_{-1.756\ (37\%)}$	9.09	$^{+1.66\ (18\%)}_{-1.98\ (22\%)}$	$^{+0.16\,(2\%)}_{-0.16\,(2\%)}$	1.89
35	3.431	$^{+2.191\ (64\%)}_{-1.256\ (37\%)}$	6.37	$^{+1.07\ (17\%)}_{-1.36\ (21\%)}$	$^{+0.11\,(2\%)}_{-0.11\,(2\%)}$	1.86
40	2.464	$^{+1.582\ (64\%)}_{-0.901\ (37\%)}$	4.51	$^{+0.72\ (16\%)}_{-0.95\ (21\%)}$	$^{+0.09\,(2\%)}_{-0.09\,(2\%)}$	1.83

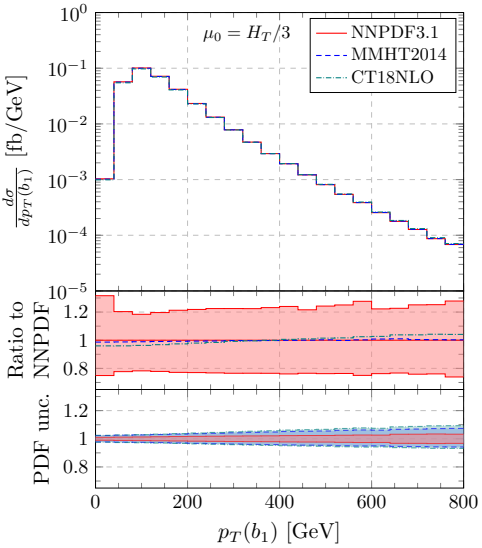
- Large NLO corrections
- 20% scale uncertainty
- mild $p_T(b)$ dependence for $\mu_0 = H_T/3$
- dominanted by real radiation
- $p_T^{\rm veto}(j) = 50$ GeV
  $K = 1.11$ & $K = 1.23$

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

Differential distributions - Uncertainties

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b} \;@\; LHC_{13TeV}$$



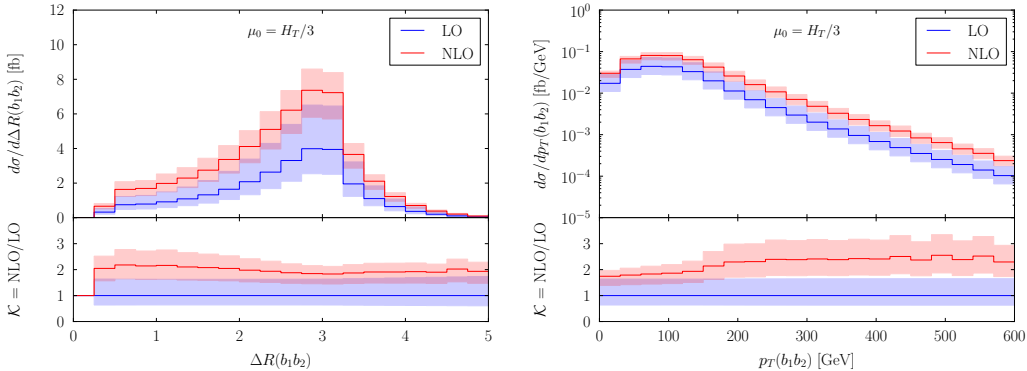


- Large shape distortions (+90% – 135%)
- Scale dependence: ±20 – 30%

- PDF uncertainties small-ish (≤ 10%)

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

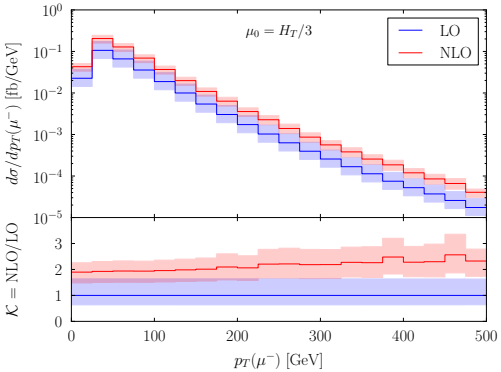
Differential distributions – b jets

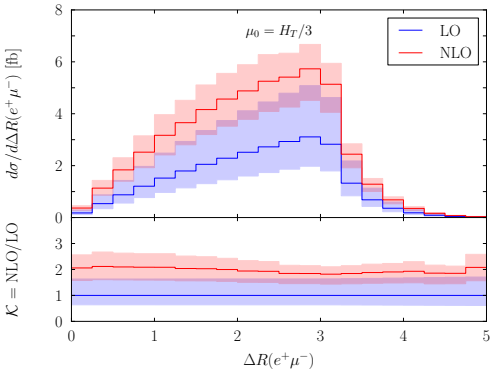


- Hardest b jets produced back-to-back → mainly from tops
- Large corrections $\sim$ 150% for $p_T(b_1 b_2)$ due to real radiation
- Scale uncertainties: 25 – 30%

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

Differential distributions – leptons





- NLO QCD corrections: 80 – 150%
- Scale uncertainties: 20 – 25%

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

Impact of b jet definitions

Can we ignore initial state b quarks in off-shell $t\bar{t}b\bar{b}$?

$$b\bar{b}/\bar{b}b \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ b\bar{b}$$
$$bb \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ bb$$
$$\bar{b}\bar{b} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ \bar{b}\bar{b}$$

$$b\bar{b}/\bar{b}b \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ b\bar{b}\ g$$
$$bb \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ bb\ g$$
$$\bar{b}\bar{b} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ \bar{b}\bar{b}\ g$$
$$bg/gb \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ b\bar{b}\ b$$
$$\bar{b}g/g\bar{b} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\ b\bar{b}\ \bar{b}$$

Assess differences in b jet def. in two schemes

charge blind

$$N_{b/\bar{b}} \geq 4$$
$$b\bar{b} \to g, \quad bg \to b, \quad \bar{b}g \to \bar{b},$$
$$bb \to g, \quad \bar{b}\bar{b} \to g$$

charge aware

$$N_b \geq 2 \ \& \ N_{\bar{b}} \geq 2$$
$$b\bar{b} \to g, \quad bg \to b, \quad \bar{b}g \to \bar{b},$$
$$bb \to b, \quad \bar{b}\bar{b} \to \bar{b}$$

Jets clustered with anti k_T jet algorithm with $R = 0.4$

Beyond NLO fixed-order $\to$ flavor k_T [Banfi,Salam,Zanderighi '06]

$\to$ flavor anti-k_T [Czakon yesterday]

Integrated fiducial cross sections

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

LO

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

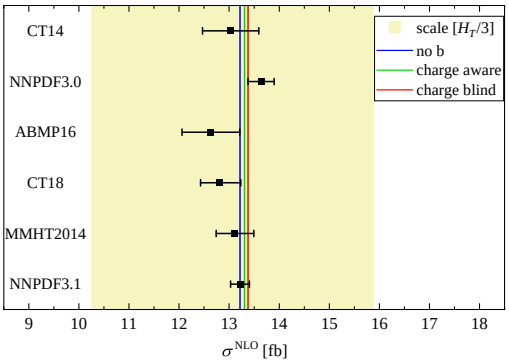
Differences are of the order of 0.2%

NLO

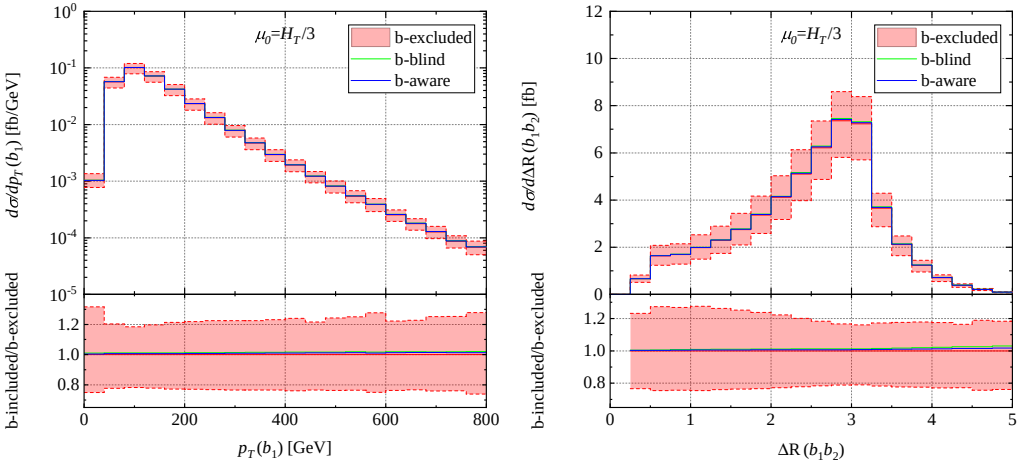
$$\sigma^{\text{NLO}}_{\text{no b}} = 13.22(3)\ \text{fb}$$
$$\sigma^{\text{NLO}}_{\text{aware}} = 13.31(3)\ \text{fb}$$
$$\sigma^{\text{NLO}}_{\text{blind}} = 13.38(3)\ \text{fb}$$

Differences are of the order of 1%

How important are these effects?



Differential distributions



- initial-state b contribution negligible
- even in extreme phase space regions $\Delta R \gtrsim 4$

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

Summary & Outlook

Summary & Outlook

Summary:

- NLO QCD corrections for off-shell $pp \to t\bar{t}b\bar{b}$
  - full off-shell effects
  - Large NLO corrections $\sim 89\%$
  - Scale uncertainties $\sim 20 - 30\%$
- Full agreement with previous calculation: `[Denner, Lang, Pellen '20]`
- Impact of intial state b quarks:
  - charge blind vs. charge aware tagging schemes
  - differences: 0.2% @ LO and 1% @ NLO
- More details: Poster session $\to$ Michele Lupattelli

Outlook:

- Comparison with Narrow Width Approximation
- Can we distinguish b jets from tops vs. prompt b jets?