NLO predictions for $t\bar{t}b\bar{b}$ production in association with a light-jet at the LHC

Federico Buccioni

in collaboration with

S. Pozzorini M. Zoller

Universität Zürich[UZH]

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

LoopFest XVII

MICHIGAN STATE UNIVERSITY

Outline

- $pp \to t\bar{t}H(H \to b\bar{b})$ at the LHC

- Open questions in theory predictions for $t\bar{t} + b$-jets production

- Scale choice and large NLO K-factor in $pp \to t\bar{t}b\bar{b}$

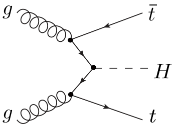
- NLO QCD predictions for $pp \to t\bar{t}b\bar{b}j$

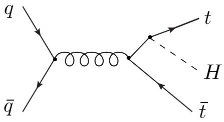
$pp \to t\bar{t}H(H \to b\bar{b})$ at the LHC

The determination of the Higgs boson coupling to the top quark is a crucial test of the SM

top quark Yukawa coupling can be determined through measurements of

$t\bar{t}H$ **associated production**



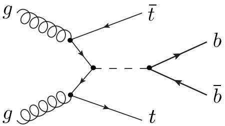


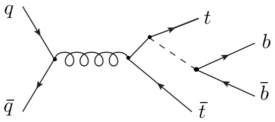
$pp \to t\bar{t}H(H \to b\bar{b})$ at the LHC

The determination of the Higgs boson coupling to the top quark is a crucial test of the SM

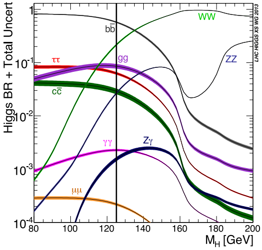
top quark Yukawa coupling can be determined through measurements of

$t\bar{t}H$ **associated production**





H branching ratio is dominated by $H \to b\bar{b}$ decay: channel with highest statistics

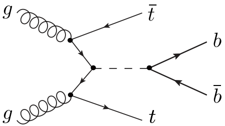


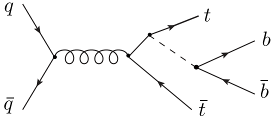
$pp \to t\bar{t}H(H \to b\bar{b})$ at the LHC

The determination of the Higgs boson coupling to the top quark is a crucial test of the SM

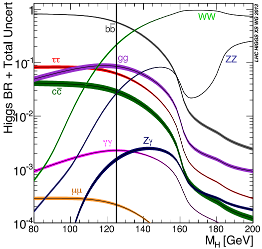
top quark Yukawa coupling can be determined through measurements of

$t\bar{t}H$ **associated production**





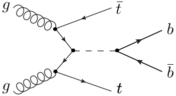
H branching ratio is dominated by $H \to b\bar{b}$ decay: channel with highest statistics



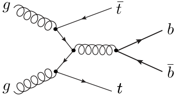
But: this channel suffers from a large, irreducible QCD background

$pp \to t\bar{t}+$ b-jets production

signal



background



An accurate understanding and description of the background is mandatory for the sensitivity of $t\bar{t}H(H \to b\bar{b})$ analyses

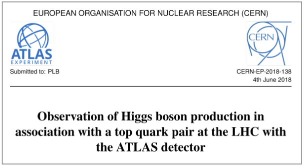
$t\bar{t}H$ discovery at the LHC

Higgs boson mass measured precisely: 125.09 ± 0.24 GeV

$\Rightarrow$ focus on **Higgs couplings**

$t\bar{t}H$ discovery at the LHC

see talks from W.C. Fisher and M.Liu



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

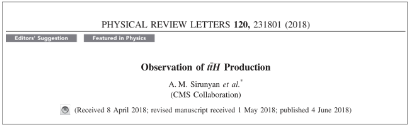
Submitted to: PLB

CERN-EP-2018-138
4th June 2018

Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector

6.3 std. dev.

5.2 std. dev.



PHYSICAL REVIEW LETTERS **120,** 231801 (2018)

Editors' Suggestion | Featured in Physics

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

(Received 8 April 2018; revised manuscript received 1 May 2018; published 4 June 2018)

$t\bar{t}H$ discovery at the LHC

Higgs boson mass measured precisely: 125.09 ± 0.24 GeV

$\Rightarrow$ focus on **Higgs couplings**

$t\bar{t}H$ discovery at the LHC

see talks from W.C. Fisher and M.Liu

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: PLB

CERN-EP-2018-138
4th June 2018

Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector

6.3 std. dev.

5.2 std. dev.

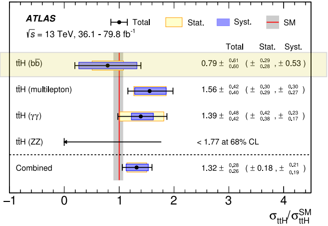
PHYSICAL REVIEW LETTERS **120**, 231801 (2018)

Editors' Suggestion Featured in Physics

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.*
(CMS Collaboration)

(Received 8 April 2018; revised manuscript received 1 May 2018; published 4 June 2018)



dominated by systematics

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, E_T^{miss}	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

uncertainty dominated by

$t\bar{t}$ + heavy flavour modelling in the $H \to b\bar{b}$ analyses

State of the art for $t\bar{t}b\bar{b}$ predictions

- First fixed order NLO QCD predictions for $pp \to t\bar{t}b\bar{b}$ [Bredenstein et al. '09, Bevilacqua et al. '09]
  first estimate of theory uncertainties + first NLO calculation for $2 \to 4$

- First NLOPS simulation for $t\bar{t}b\bar{b}$ production in `Powhel` [Garzelli et al. '13]
  ME in the 5F scheme ($m_b = 0$) + Powheg matching for the parton shower
  since recently available also in the 4F scheme [Bevilacqua et al. '17]

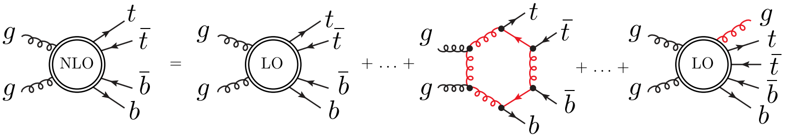
- NLOPS generator for $t\bar{t}b\bar{b}$ with massive b-quark in `OpenLoops+Sherpa` [Cascioli et al. '14]
  `OpenLoops` for 1-loop automation + `Sherpa` employing MC@NLO matching

- NLOPS generator for $t\bar{t}$ + b-jet production in 4F scheme in `OpenLoops+Powheg` [Ježo et al. '18]
  `OpenLoops` for amplitudes automation + Powheg matching in `Powheg-Box-Res`

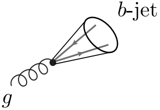
  thorough investigation of uncertainties related to matching method
  and parton shower modelling

- $t\bar{t}$ + b-jets simulations in the 4F scheme also available in
  `MG5_aMC@NLO` [Alwall et al. '14] and `Matchbox` [Plaetzer, Reuschle et al.]

$t\bar{t} + b$-jets production in the 4F scheme



We work in the **4F scheme**: ***b*-quarks** are treated as **massive**



⇒ calculation of the ME can be extended to the entire the phase space

⇒ no singularities in $g \to b\bar{b}$ splittings. Safe collinear regime with $g \to b$-jet

On the other hand:

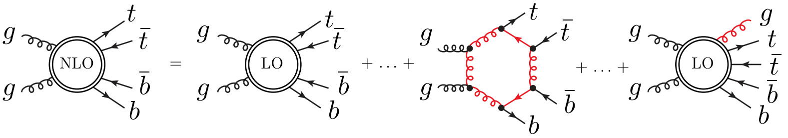
× non-trivial multi-scale multi-particle QCD process

× large scales separation between $t\bar{t}$ and $b\bar{b}$ systems

$m_b \sim 5$ GeV $\qquad$ $t\bar{t}$ typical scale up to ~ 500 GeV

scale choice and estimation of theoretical uncertainties non trivial

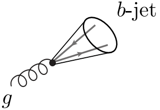
$t\bar{t}$ + b-jets production in the 4F scheme



We work in the **4F scheme**: **b-quarks** are treated as **massive**

$\Rightarrow$ calculation of the ME can be extended to the entire the phase space

$\Rightarrow$ no singularities in $g \to b\bar{b}$ splittings. Safe collinear regime with $g \to b$-jet



On the other hand:

× non-trivial multi-scale multi-particle QCD process

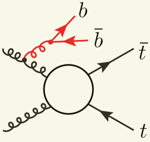
× large scales separation between $t\bar{t}$ and $b\bar{b}$ systems

$m_b \sim 5$ GeV $\quad$ $t\bar{t}$ typical scale up to ~ 500 GeV

scale choice and estimation of theoretical uncertainties non trivial

XS dominated by FS $g \to b\bar{b}$ splittings

[Ježo et al. '18]



it supports using $m_b > 0$

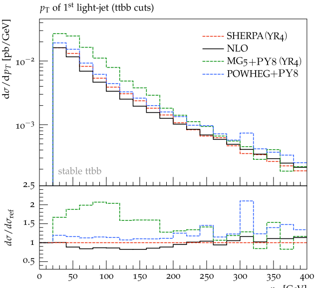
Discrepancies in $t\bar{t}b\bar{b}$ NLOPS generators

Standard factor-2 μ_R variations $\sim 30\%$ NLO scale dependence

But: discrepancies between different NLOPS generators significantly exceed NLO scale variations

Most sensitive distribution: light-jet p_T spectrum

up to 100% shape differences in the 100-200 GeV region



Plot by T. Ježo

Most likely **hypothesis** on origin of NLOPS differences:

interplay between PS and large NLO $t\bar{t}b\bar{b}$ K-factor

$\Rightarrow$ it enters the PS matching in the soft regime

origin of large K-factor to be understood

Idea: reduce uncertainties discarding less accurate NLOPS predictions by means of a benchmark $p_{T,j}$ with uncertainty well below 100%

This talk

Motivation for $pp \to t\bar{t}b\bar{b}j$ at NLO QCD

Large NLO K-factor

Input parameters, PDFs and scale choices [Ježo et al. '18]

$$m_b = 4.75 \text{ GeV} \qquad m_t = 172.5 \text{ GeV}$$

dynamic scales

$$\mu_R = \sqrt{\mu_{t\bar{t}}\mu_{b\bar{b}}} \quad \text{with} \quad \mu_{b\bar{b}} = \sqrt{E_{T,b}E_{T,\bar{b}}} \quad \mu_{t\bar{t}} = \sqrt{E_{T,t}E_{T,\bar{t}}}$$

$$\mu_F = \frac{H_T}{2} = \frac{1}{2}\sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i}$$

NLO PDFs are used throughout: both at LO and NLO

`NNPDF_nlo_as_0118_nf_4` with $\alpha_s^{4\mathrm{f}}$

Large NLO K-factor

Input parameters, PDFs and scale choices [Ježo et al. '18]

$$m_b = 4.75 \text{ GeV} \qquad m_t = 172.5 \text{ GeV}$$

dynamic scales

$$\mu_R = \sqrt{\mu_{t\bar{t}}\mu_{b\bar{b}}} \quad \text{with} \quad \mu_{b\bar{b}} = \sqrt{E_{T,b}E_{T,\bar{b}}} \quad \mu_{t\bar{t}} = \sqrt{E_{T,t}E_{T,\bar{t}}}$$

$$\mu_F = \frac{H_T}{2} = \frac{1}{2}\sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i}$$

NLO PDFs are used throughout: both at LO and NLO

`NNPDF_nlo_as_0118_nf_4` with α_s^{4f}

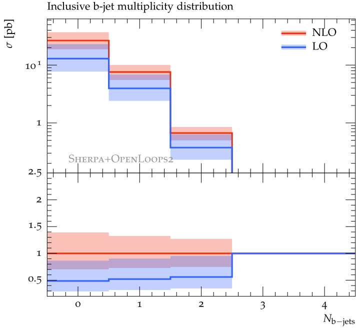
The NLO QCD cross sections for $pp \to t\bar{t}b\bar{b}$ feature a large K-factor

K-factor

$N_{b-jets\geq 0}$: 2.06

$N_{b-jets\geq 1}$: 1.92

$N_{b-jets\geq 2}$: 1.79



Large NLO K-factor

Input parameters, PDFs and scale choices [Ježo et al. '18]

$$m_b = 4.75 \text{ GeV} \qquad m_t = 172.5 \text{ GeV}$$

dynamic scales

$$\mu_R = \sqrt{\mu_{t\bar{t}}\mu_{b\bar{b}}} \quad \text{with} \quad \mu_{b\bar{b}} = \sqrt{E_{T,b}E_{T,\bar{b}}} \quad \mu_{t\bar{t}} = \sqrt{E_{T,t}E_{T,\bar{t}}}$$

$$\mu_F = \frac{H_T}{2} = \frac{1}{2}\sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i}$$

NLO PDFs are used throughout: both at LO and NLO

`NNPDF_nlo_as_0118_nf_4` with α_s^{4f}

The NLO QCD cross sections for $pp \to t\bar{t}b\bar{b}$ feature a large K-factor

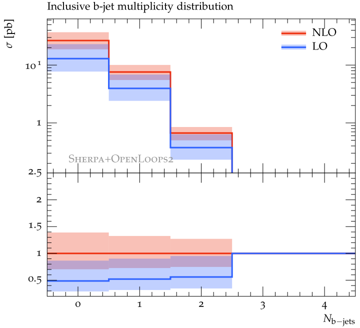
more realistic picture of perturbative convergence but much bigger K-factor wrt using LO α_S + PDFs for σ_{LO}

K-factor

$N_{b-jets\geq 0}$: 2.06

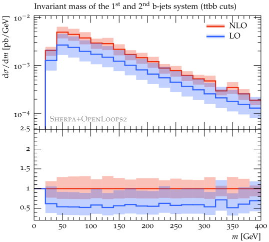
$N_{b-jets\geq 1}$: 1.92

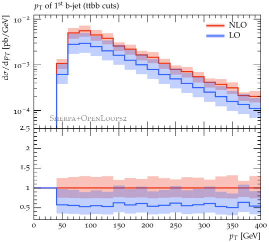
$N_{b-jets\geq 2}$: 1.79



Large NLO K-factor

K-factor is large and stable for inclusive and exclusive observables





Such a large K-factor poses a question:

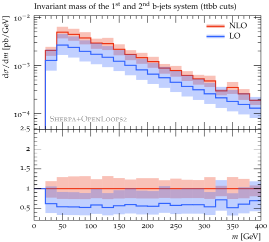
are corrections beyond NLO larger than factor 2 scale variations?

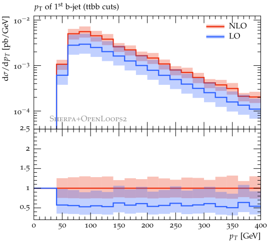
↓

origin of large K-factor needs to be understood

Large NLO K-factor

K-factor is large and stable for inclusive and exclusive observables





Such a large K-factor poses a question:

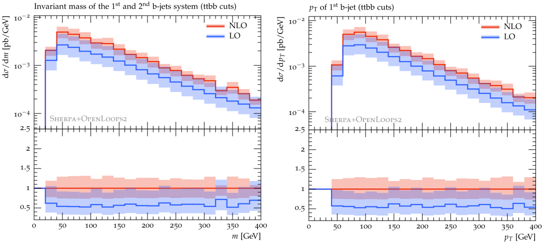
are corrections beyond NLO larger than factor 2 scale variations?

origin of large K-factor needs to be understood

Hypotheses on origin of large K-factor:

Large NLO K-factor

K-factor is large and stable for inclusive and exclusive observables



Such a large K-factor poses a question:

are corrections beyond NLO larger than factor 2 scale variations?

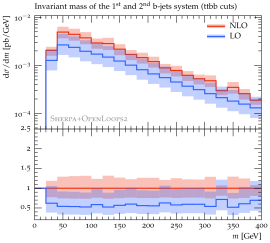
origin of large K-factor needs to be understood

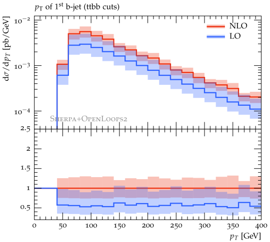
Hypotheses on origin of large K-factor:

(a) sizeable NLO real emission contribution
large mass gap in $t\bar{t}$ and $b\bar{b}$ systems (m_b, $p_{T,b} \ll m_t$),
σ_{NLO} strongly enhanced by hard j radiation ($m_t > p_{T,j} > p_{T,b}$)

Large NLO K-factor

K-factor is large and stable for inclusive and exclusive observables





Such a large K-factor poses a question:

are corrections beyond NLO larger than factor 2 scale variations?

↓

origin of large K-factor needs to be understood

Hypotheses on origin of large K-factor:

(a) sizeable NLO real emission contribution
large mass gap in $t\bar{t}$ and $b\bar{b}$ systems (m_b, $p_{T,b} \ll m_t$),
σ_{NLO} strongly enhanced by hard j radiation ($m_t > p_{T,j} > p_{T,b}$)

→ may be interpreted as $t\bar{t}gg(g \to b\bar{b})$

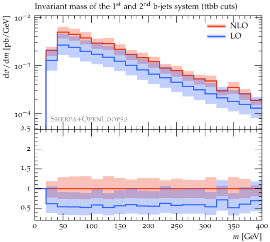
described at LO

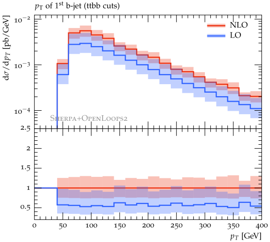
↓

potentially large corrections beyond NLO

Large NLO K-factor

K-factor is large and stable for inclusive and exclusive observables





Such a large K-factor poses a question:

are corrections beyond NLO larger than factor 2 scale variations?

↓

origin of large K-factor needs to be understood

Hypotheses on origin of large K-factor:

(a) sizeable NLO real emission contribution
large mass gap in $t\bar{t}$ and $b\bar{b}$ systems (m_b, $p_{T,b} \ll m_t$),
σ_{NLO} strongly enhanced by hard j radiation ($m_t > p_{T,j} > p_{T,b}$)

(b) a non-optimal μ_R scale choice

may be interpreted as $t\bar{t}gg(g \to b\bar{b})$

↓

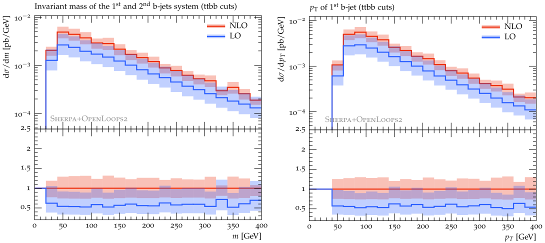
described at LO

↓

potentially large corrections beyond NLO

Large NLO K-factor

K-factor is large and stable for inclusive and exclusive observables



Such a large K-factor poses a question:

are corrections beyond NLO larger than factor 2 scale variations?

↓

origin of large K-factor needs to be understood

Hypotheses on origin of large K-factor:

(a) sizeable NLO real emission contribution
large mass gap in $t\bar{t}$ and $b\bar{b}$ systems $(m_b,\, p_{T,b} \ll m_t)$,
σ_{NLO} strongly enhanced by hard j radiation $(m_t > p_{T,j} > p_{T,b})$

→ may be interpreted as $t\bar{t}gg(g \to b\bar{b})$

↓ described at LO

↓ potentially large corrections beyond NLO

(b) a non-optimal μ_R scale choice

→ a more appropriate μ_R choice might reduce the K-factor and also mitigate the NLOPS discrepancies

Mass effects on $pp \to t\bar{t}b\bar{b}$ cross sections

Aim: try to understand if the large K-factor is related to $m_t \gg m_b$

Idea: study the behaviour of the NLO K-factor for different mass configurations using an "interpolating" mass $m^* = \sqrt{m_b m_t} \sim 28.62$ GeV

masses [GeV]		$\sigma_{N_{b\text{-jets}\geq 0}}$ [pb]			$\sigma_{N_{b\text{-jets}\geq 1}}$ [pb]			$\sigma_{N_{b\text{-jets}\geq 2}}$ [pb]		
m_b	m_t	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$
4.75	172.5	12.94	26.61	2.06	3.955	7.593	1.92	0.374	0.669	1.79
28.62	28.62	321.1	642.4	2.0	165.3	317.7	1.92	34.61	63.42	1.83
28.62	172.5	0.999	1.911	1.9	0.752	1.400	1.86	0.245	0.437	1.78
172.5	172.5	0.013	0.023	1.82	0.013	0.023	1.81	$9.31 \cdot 10^{-3}$	$1.67 \cdot 10^{-2}$	1.79

Dynamic scales choice:

$$\mu_R = \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$$

$$\mu_F = \frac{H_T}{2}$$

Mass effects on $pp \to t\bar{t}b\bar{b}$ cross sections

Aim: try to understand if the large K-factor is related to $m_t \gg m_b$

Idea: study the behaviour of the NLO K-factor for different mass configurations using an "interpolating" mass $m^* = \sqrt{m_b m_t} \sim 28.62$ GeV

masses [GeV]		$\sigma_{N_{b\text{-jets}\geq 0}}$ [pb]			$\sigma_{N_{b\text{-jets}\geq 1}}$ [pb]			$\sigma_{N_{b\text{-jets}\geq 2}}$ [pb]		
m_b	m_t	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$
4.75	172.5	12.94	26.61	2.06	3.955	7.593	1.92	0.374	0.669	1.79
28.62	28.62	321.1	642.4	2.0	165.3	317.7	1.92	34.61	63.42	1.83
28.62	172.5	0.999	1.911	1.9	0.752	1.400	1.86	0.245	0.437	1.78
172.5	172.5	0.013	0.023	1.82	0.013	0.023	1.81	$9.31 \cdot 10^{-3}$	$1.67 \cdot 10^{-2}$	1.79

Dynamic scales choice:

$$\mu_R = \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$$

$$\mu_F = \frac{H_T}{2}$$

× Large K-factor stable wrt variations of m_t, m_b gap
⇒ hypothesis (a) disfavoured

Mass effects on $pp \to t\bar{t}b\bar{b}$ cross sections

Aim: try to understand if the large K-factor is related to $m_t \gg m_b$

Idea: study the behaviour of the NLO K-factor for different mass configurations using an "interpolating" mass $m^* = \sqrt{m_b m_t} \sim 28.62$ GeV

masses [GeV]		$\sigma_{N_{b\text{-jets}\geq 0}}$ [pb]			$\sigma_{N_{b\text{-jets}\geq 1}}$ [pb]			$\sigma_{N_{b\text{-jets}\geq 2}}$ [pb]		
m_b	m_t	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$
4.75	172.5	12.94	26.61	2.06	3.955	7.593	1.92	0.374	0.669	1.79
28.62	28.62	321.1	642.4	2.0	165.3	317.7	1.92	34.61	63.42	1.83
28.62	172.5	0.999	1.911	1.9	0.752	1.400	1.86	0.245	0.437	1.78
172.5	172.5	0.013	0.023	1.82	0.013	0.023	1.81	$9.31 \cdot 10^{-3}$	$1.67 \cdot 10^{-2}$	1.79

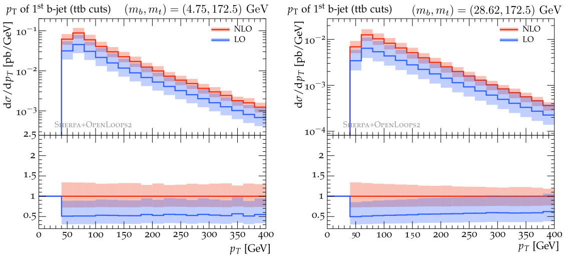
Dynamic scales choice:

$$\mu_R = \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$$

$$\mu_F = \frac{H_T}{2}$$

× Large K-factor stable wrt variations of m_t, m_b gap
⇒ hypothesis (a) disfavoured

✓ good shapes in distributions



Fixed vs dynamic μ_R scale choice

If no mass gap i.e. $m_b = m_t$ there would be a natural choice $\Rightarrow \mu_R = m_t$

A direct generalization could be $\mu_R = \sqrt{m_b m_t}$ ⟶ moderate K-factor for different m_b, m_t

Fixed vs dynamic μ_R scale choice

If no mass gap i.e. $m_b = m_t$ there would be a natural choice $\Rightarrow \mu_R = m_t$

A direct generalization could be $\mu_R = \sqrt{m_b m_t}$ → moderate K-factor for different m_b, m_t

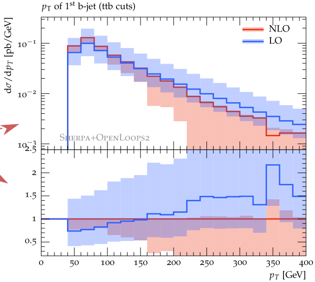
Physical case: $m_b = 4.75$ GeV, $m_t = 172.5$ GeV

$\sqrt{m_b m_t} \sim 28.62$ GeV and K-factor ~ 1.47

✓ reduced K-factor

× enhanced shape distortion in distributions

× unreliable scale uncertainties



Fixed vs dynamic μ_R scale choice

If no mass gap i.e. $m_b = m_t$ there would be a natural choice $\Rightarrow \mu_R = m_t$

A direct generalization could be $\mu_R = \sqrt{m_b m_t}$ → moderate K-factor for different m_b, m_t

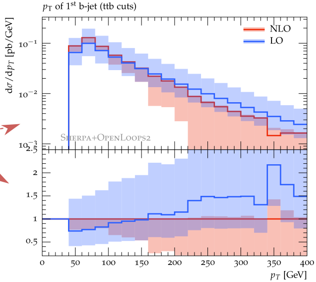
Physical case: $m_b = 4.75$ GeV, $m_t = 172.5$ GeV

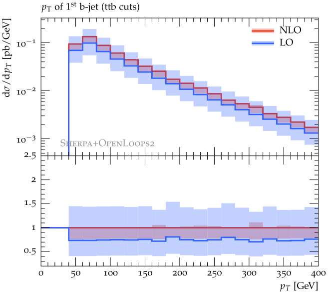
$\sqrt{m_b m_t} \sim 28.62$ GeV and K-factor ~ 1.47

✓ reduced K-factor

× enhanced shape distortion in distributions

× unreliable scale uncertainties





motivates a reduced dynamic μ_R

Example: factor 3 reduction of μ_R

✓ reduced K-factor

✓ no shape distortionsin distributions

✓ $\sim 20\%$ scale uncertainties

Renormalisation scale dependence

Both at LO and NLO scale uncertainties are dominated by μ_R variations.

Default choice of scale: $\mu_R = \mu_{def} \equiv \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

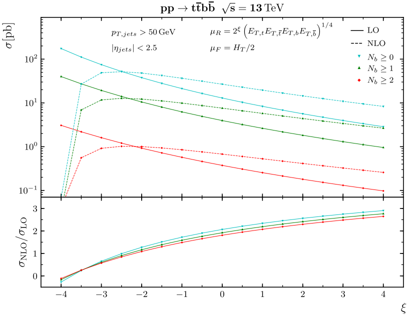
Average value $\bar{\mu}_{def} \Rightarrow \quad N_{b\geq 0} \sim 73$ GeV $\quad N_{b\geq 1} \sim 93$ GeV $\quad N_{b\geq 2} \sim 124$ GeV

Renormalisation scale dependence

Both at LO and NLO scale uncertainties are dominated by μ_R variations.

Default choice of scale: $\mu_R = \mu_{def} \equiv \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

Average value $\bar{\mu}_{def} \Rightarrow$ $N_{b\geq 0} \sim 73$ GeV $N_{b\geq 1} \sim 93$ GeV $N_{b\geq 2} \sim 124$ GeV



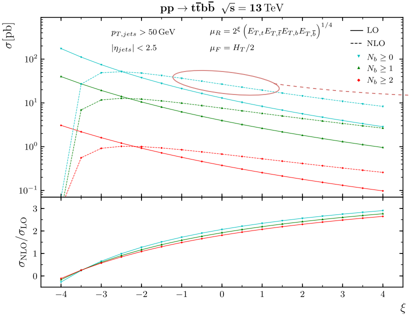
$$\mu_R = 2^\xi \left(E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}}\right)^{1/4}$$

Renormalisation scale dependence

Both at LO and NLO scale uncertainties are dominated by μ_R variations.

Default choice of scale: $\mu_R = \mu_{def} \equiv \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

Average value $\bar{\mu}_{def} \Rightarrow$ $N_{b\geq 0} \sim 73$ GeV $N_{b\geq 1} \sim 93$ GeV $N_{b\geq 2} \sim 124$ GeV



$\mu_R = 2^{\xi} \left(E_{T,t} E_{T,\bar{t}} E_{T,b} E_{T,\bar{b}}\right)^{1/4}$

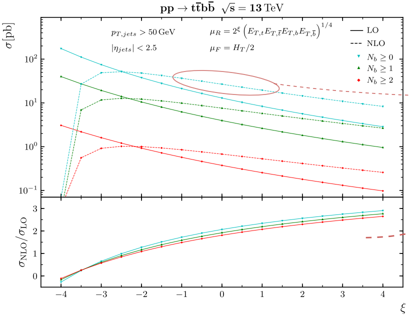
factor 2 variation: $\sim 27\%$ NLO uncertainty

Renormalisation scale dependence

Both at LO and NLO scale uncertainties are dominated by μ_R variations.

Default choice of scale: $\mu_R = \mu_{def} \equiv \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

Average value $\bar{\mu}_{def} \Rightarrow$ $N_{b\geq 0} \sim 73$ GeV $N_{b\geq 1} \sim 93$ GeV $N_{b\geq 2} \sim 124$ GeV



$\mu_R = 2^\xi \left(E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}}\right)^{1/4}$

factor 2 variation: $\sim 27\%$ NLO uncertainty

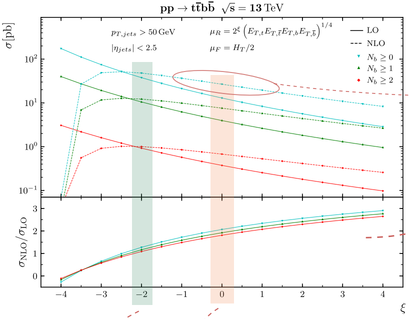
similar K-factor for different b-jets multiplicities

Renormalisation scale dependence

Both at LO and NLO scale uncertainties are dominated by μ_R variations.

Default choice of scale: $\mu_R = \mu_{def} \equiv \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

Average value $\bar{\mu}_{def} \Rightarrow$ $N_{b\geq 0} \sim 73$ GeV $N_{b\geq 1} \sim 93$ GeV $N_{b\geq 2} \sim 124$ GeV



$\mu_R = 2^\xi \left(E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}}\right)^{1/4}$

factor 2 variation: $\sim 27\%$ NLO uncertainty

similar K-factor for different b-jets multiplicities

default

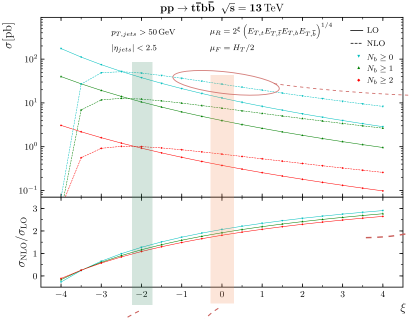
region where K-factor ~ 1, close the maximum of the NLO XS

Renormalisation scale dependence

Both at LO and NLO scale uncertainties are dominated by μ_R variations.

Default choice of scale: $\mu_R = \mu_{def} \equiv \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

Average value $\bar{\mu}_{def} \Rightarrow$ $N_{b\geq 0} \sim 73$ GeV $N_{b\geq 1} \sim 93$ GeV $N_{b\geq 2} \sim 124$ GeV



$\mu_R = 2^{\xi}\left(E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}}\right)^{1/4}$

factor 2 variation: $\sim 27\%$ NLO uncertainty

similar K-factor for different b-jets multiplicities

a factor 2-4 reduction of μ_R brings K-factor close to 1 and scale uncertainty $\sim 20\%$

default

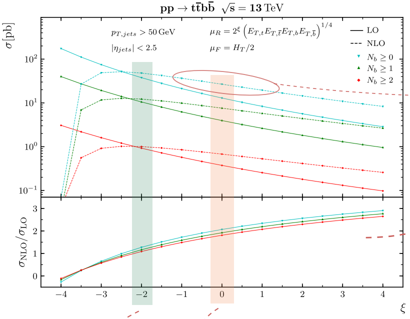
region where K-factor ~ 1, close the maximum of the NLO XS

Renormalisation scale dependence

Both at LO and NLO scale uncertainties are dominated by μ_R variations.

Default choice of scale: $\mu_R = \mu_{def} \equiv \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

Average value $\bar{\mu}_{def} \Rightarrow$ $N_{b\geq 0} \sim 73$ GeV $N_{b\geq 1} \sim 93$ GeV $N_{b\geq 2} \sim 124$ GeV



$\mu_R = 2^\xi \left(E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}}\right)^{1/4}$

factor 2 variation: $\sim 27\%$ NLO uncertainty

similar K-factor for different b-jets multiplicities

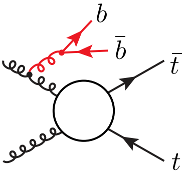
a factor 2-4 reduction of μ_R brings K-factor close to 1 and scale uncertainty $\sim 20\%$

default

region where K-factor ~ 1, close the maximum of the NLO XS

it seems to support hypothesis (b)

Alternative μ_R choice



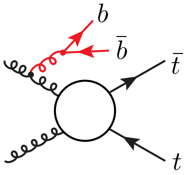
Alternative μ_R based on k_T of splittings in dominant $t\bar{t}b\bar{b}$ topologies

$$\mu_R = \mu_{gbb} \equiv \left(E_{T,t} E_{T,\bar{t}} E_{T,b\bar{b}}\, m_{b\bar{b}}\right)^{1/4}$$

In general it is a harder scale than μ_{def}: $\bar{\mu}_{gbb} \sim 125$ GeV $\bar{\mu}_{def} \sim 93$ GeV

→ hence a larger K-factor than μ_{def} at central value

Alternative μ_R choice



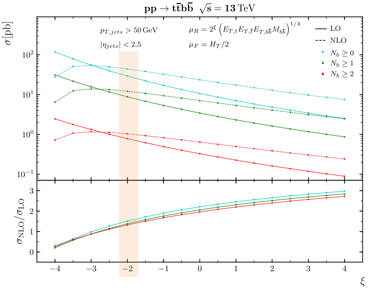
Alternative μ_R based on k_T of splittings in dominant $t\bar{t}b\bar{b}$ topologies

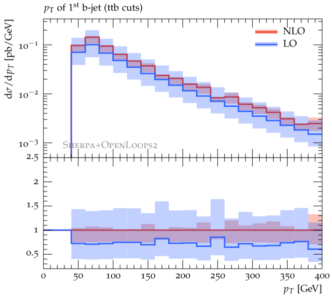
$$\mu_R = \mu_{gbb} \equiv \left(E_{T,t}E_{T,\bar{t}}E_{T,b\bar{b}}\, m_{b\bar{b}}\right)^{1/4}$$

In general it is a harder scale than μ_{def}: $\bar{\mu}_{gbb} \sim 125$ GeV $\bar{\mu}_{def} \sim 93$ GeV

→ hence a larger K-factor than μ_{def} at central value

Example: $\frac{\mu_{gbb}}{4} \Rightarrow K$-factor ~ 1.4 yields 20-25% scale uncertainty at NLO





✓ good shape of K-factor for relevant distributions

$pp \to t\bar{t}b\bar{b}j$ at NLO QCD

Disclaimer: all results are preliminary!

$pp \to t\bar{t}b\bar{b}j$ at NLO QCD

Disclaimer: all results are preliminary!

First jet emission from matrix element $\Rightarrow$ accurate benchmark for p_T of light jet radiation

$pp \to t\bar{t}b\bar{b}j$ at NLO QCD

Disclaimer: all results are preliminary!

First jet emission from matrix element $\Rightarrow$ accurate benchmark for p_T of light jet radiation

We consider $pp \to t\bar{t}b\bar{b}j$ at 13 TeV centre of mass energy

- top quark stable, not decayed
- jets reconstructed using anti-k_T algorithm
  as implemented in `FastJet-3.2`
- $\Delta R = 0.4, \quad p_T > 50$ GeV, $\quad |\eta| < 2.5$
- input parameters and scales choice
  choice as in $t\bar{t}b\bar{b}$

$pp \to t\bar{t}b\bar{b}j$ at NLO QCD

Disclaimer: all results are preliminary!

First jet emission from matrix element $\Rightarrow$ accurate benchmark for p_T of light jet radiation

We consider $pp \to t\bar{t}b\bar{b}j$ at 13 TeV centre of mass energy

- top quark stable, not decayed
- jets reconstructed using anti-k_T algorithm as implemented in `FastJet-3.2`
- $\Delta R = 0.4, \quad p_T > 50$ GeV, $\quad |\eta| < 2.5$
- input parameters and scales choice choice as in $t\bar{t}b\bar{b}$

b-jets tagging

"single-tagged": b or $\bar{b}$ quark content

"double-tagged": $b\bar{b}$ content

generic *b*-jet: b, $\bar{b}$ and $b\bar{b}$ equally counted

this talk (→ generic *b*-jet)

important for comparisons against PS (→ "double-tagged")

OpenLoops2 for $t\bar{t}b\bar{b}j$ 1-loop MEs

The 1-loop matrix elements relevant for $t\bar{t}b\bar{b}$ and $t\bar{t}b\bar{b}j$ production are computed using

`OpenLoops2`: new on-the-fly helicity summation and integrand reduction [F.B., S.Pozzorini, M.Zoller '17]

see talk from Max Zoller

The full hadronic prediction is provided through `OpenLoops2` + `SHERPA-2.2.4`

same interface as OL1

OpenLoops2 for $t\bar{t}b\bar{b}j$ 1-loop MEs

The 1-loop matrix elements relevant for $t\bar{t}b\bar{b}$ and $t\bar{t}b\bar{b}j$ production are computed using

OpenLoops2: new on-the-fly helicity summation and integrand reduction [F.B., S.Pozzorini, M.Zoller '17]

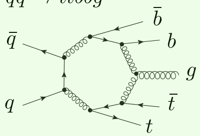
see talk from Max Zoller

The full hadronic prediction is provided through OpenLoops2 + SHERPA-2.2.4

same interface as OL1

In the 4F scheme there are two main partonic channels (+ crossings):

$q\bar{q} \to t\bar{t}b\bar{b}g$

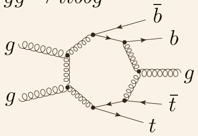


- up to rank 4 7-point 1-loop integrals
- 3534 1L Feyn. diags.
- 2^6 relevant helicity configurations

Timings[s/point] (colour + helicity sums)

	OL1	OL2+Collier	OL2+OFR
$m_b = 0$	0.337	0.208	0.233
$m_b \neq 0$	0.593	0.269	0.297

$gg \to t\bar{t}b\bar{b}g$



- up to rank 5 7-point 1-loop integrals
- 25431 1L Feyn. diags.
- 2^7 relevant helicity configurations

Timings[s/point]

	OL1	OL2+Collier	OL2+OFR
$m_b = 0$	4.671	1.877	2.141
$m_b \neq 0$	8.706	2.650	2.958

OpenLoops2 for $t\bar{t}b\bar{b}j$ 1-loop MEs

The 1-loop matrix elements relevant for $t\bar{t}b\bar{b}$ and $t\bar{t}b\bar{b}j$ production are computed using

`OpenLoops2`: new on-the-fly helicity summation and integrand reduction [F.B., S.Pozzorini, M.Zoller '17]

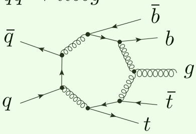
see talk from Max Zoller

The full hadronic prediction is provided through `OpenLoops2` + `SHERPA-2.2.4`

same interface as OL1

In the 4F scheme there are two main partonic channels (+ crossings):

$q\bar{q} \to t\bar{t}b\bar{b}g$

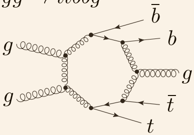


- up to rank 4 7-point 1-loop integrals
- 3534 1L Feyn. diags.
- 2^6 relevant helicity configurations

Timings[s/point] (colour + helicity sums)

	OL1	OL2+Collier	OL2+OFR
$m_b = 0$	0.337	0.208	0.233
$m_b \neq 0$	0.593	0.269	0.297

$gg \to t\bar{t}b\bar{b}g$



- up to rank 5 7-point 1-loop integrals
- 25431 1L Feyn. diags.
- 2^7 relevant helicity configurations

Timings[s/point]

	OL1	OL2+Collier	OL2+OFR
$m_b = 0$	4.671	1.877	2.141
$m_b \neq 0$	8.706	2.650	2.958

$+75 - 85\%$

$\sim +40\%$

OL1/OL2 up to 3!

SHERPA + OpenLoops2

$$\sigma_n^{\text{NLO}} = \int \mathrm{d}\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n)\right] + \int \mathrm{d}\Phi_{n+1} \mathcal{R}(\Phi_{n+1})$$

Dipole subtraction method [Catani, Seymour '96]: factorisation and universality of IR singularities

$$\mathcal{R}(\Phi_{n+1}) \to \mathcal{B} \otimes \mathcal{S}(\Phi_1) \qquad \mathcal{I} = \int \mathrm{d}\Phi_1 \mathcal{S}(\Phi_1) \Rightarrow \text{integrated analytically}$$

It allows for an IR safe numerical integration of the cross section

$$\sigma_n^{\text{NLO}} = \int \mathrm{d}\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \mathcal{B}(\Phi_n) \otimes \mathcal{I}\right] + \int \mathrm{d}\Phi_{n+1} \left[\mathcal{R}(\Phi_{n+1}) - \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1)\right]$$

SHERPA + OpenLoops2

$$\sigma_n^{\text{NLO}} = \int d\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n)\right] + \int d\Phi_{n+1} \mathcal{R}(\Phi_{n+1})$$

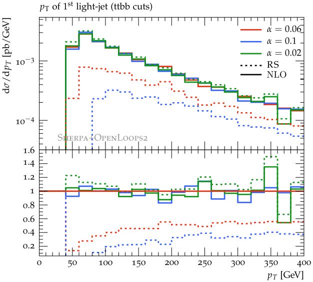
Dipole subtraction method [Catani, Seymour '96]: factorisation and universality of IR singularities

$$\mathcal{R}(\Phi_{n+1}) \to \mathcal{B} \otimes \mathcal{S}(\Phi_1) \qquad \mathcal{I} = \int d\Phi_1 \mathcal{S}(\Phi_1) \Rightarrow \text{integrated analytically}$$

It allows for an IR safe numerical integration of the cross section

$$\sigma_n^{\text{NLO}} = \int d\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \mathcal{B}(\Phi_n) \otimes \mathcal{I}\right] + \int d\Phi_{n+1} \left[\mathcal{R}(\Phi_{n+1}) - \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1)\right]$$

In `Sherpa` the dipole phase space can be restricted by means of `DIPOLE_ALPHA`



Varying α offers a check of the consistency of the subtraction

first validation of the calculation ✓

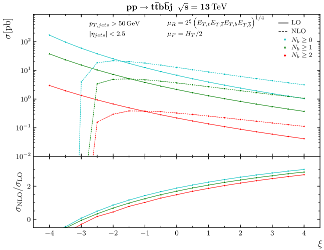
α	NLO[pb]	BVI[pb]	RS[pb]
0.02	$3.253 \cdot 10^{-1}$	$-0.32 \cdot 10^{-1}$	$3.57 \cdot 10^{-1}$
0.06	$3.266 \cdot 10^{-1}$	$1.97 \cdot 10^{-1}$	$1.30 \cdot 10^{-1}$
0.1	$3.247 \cdot 10^{-1}$	$2.73 \cdot 10^{-1}$	$0.52 \cdot 10^{-1}$

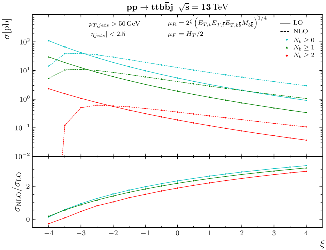
$N_{b\text{-jets}\geq 2}$ XS

$pp \to t\bar{t}b\bar{b}j$ cross sections at 13 TeV

	$\sigma_{N_{b\text{-jets}}\geq 1}$ [pb]			$\sigma_{N_{b\text{-jets}}\geq 2}$ [pb]		
Process	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$
$t\bar{t}b\bar{b},\ \mu_{def}$	$3.955^{+73\%}_{-39\%}$	$7.593^{+32\%}_{-27\%}$	1.92	$0.374^{+69\%}_{-38\%}$	$0.669^{+27\%}_{-25\%}$	1.79
$t\bar{t}b\bar{b},\ \mu_{gbb}$	$3.441^{+70\%}_{-38\%}$	$7.089^{+37\%}_{-28\%}$	2.06	$0.327^{+67\%}_{-37\%}$	$0.642^{+33\%}_{-27\%}$	1.96
$t\bar{t}b\bar{b}j,\ \mu_{def}$	$2.164^{+96\%}_{-45\%}$	$3.670^{+27\%}_{-30\%}$	1.70	$0.219^{+90\%}_{-44\%}$	$0.327^{+12\%}_{-25\%}$	1.49
$t\bar{t}b\bar{b}j,\ \mu_{gbb}$	$1.894^{+93\%}_{-45\%}$	$4.120^{+46\%}_{-34\%}$	2.17	$0.188^{+87\%}_{-43\%}$	$0.354^{+36\%}_{-30\%}$	1.88

- Scale uncertainty dominated by μ_R variations (as in $t\bar{t}b\bar{b}$)
- For $pp \to t\bar{t}b\bar{b}j$ $\sigma_{LO} \propto \alpha_s^5$ up to $\sim 90 - 95\%$ scale uncertainty





K**-factor**:

- slightly smaller wrt $t\bar{t}b\bar{b}$ but still significant
- quite large for μ_{gbb} bit smaller for μ_{def}
- can be reduced by rescaling the central value

b-jets distributions

We consider the phase space with two resolved b-jets

K-factor

- quite stable for both scale choices
- though more stable for μ_{gbb} over the full spectrum

Scale uncertainty at NLO

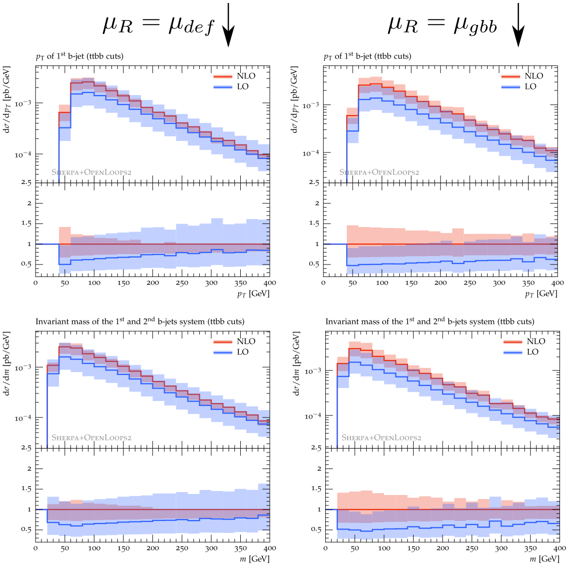
- compatible with uncertainty on the cross section:

  ranges in $\sim$ 10-25% for μ_{def}

  lives around 35% for μ_{gbb}

- for both scale choices, the uncertainty reduces in the tails
- μ_{def} shows a smaller scale uncertainty overall

  due to $\bar{\mu}_{def} < \bar{\mu}_{gbb}$



Light-jet p_T spectrum at NLO

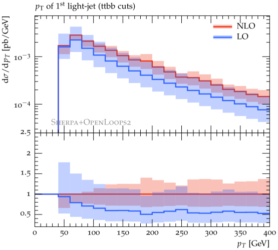
K-factor

- significant shape distortions for μ_{def} below 100-200 GeV
- more stable for μ_{gbb}

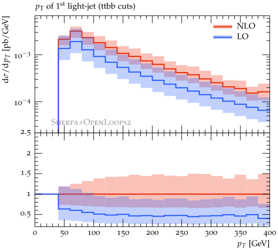
Scale uncertainty at NLO

- contrary to b-jet distribution it increases in the tail up to 40%-50%

$\mu_R = \mu_{def}$

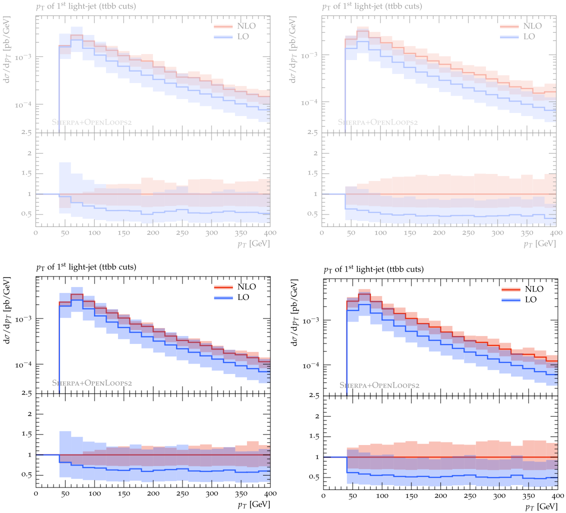


$\mu_R = \mu_{gbb}$



Light-jet p_T spectrum at NLO

$\mu_R = \mu^j_{def}$ $\mu_R = \mu^j_{gbb}$



Scale choices which include jet p_T

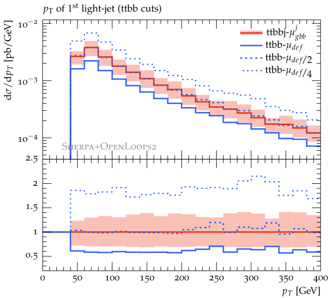
$$\mu^j_{def} = (E_{T,t} E_{T,\bar{t}} E_{T,b} E_{T,\bar{b}}\, p_{T,j})^{1/5}$$

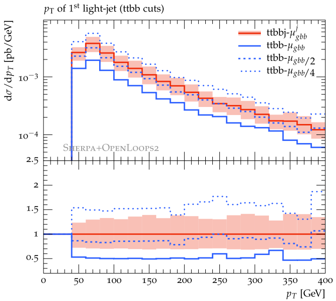
$$\mu^j_{gbb} = (E_{T,t} E_{T,\bar{t}} M_{T,b\bar{b}} E_{T,b\bar{b}}\, p_{T,j})^{1/5}$$

tends to reduce NLO uncertainties and shape distortions especially with μ_{gbb}

$t\bar{t}b\bar{b}$ vs $t\bar{t}b\bar{b}j$ NLO predictions for $p_{T,j}$

Reference scale choice: $\mu_R = \mu^j{}_{gbb} \equiv (E_{T,t} E_{T,\bar{t}}\, m_{b\bar{b}} E_{T,b\bar{b}}\, p_{T,j})^{1/5}$





- ✓ remarkably good shape agreement over all the p_T spectrum
- ✓ rescaling μ_{gbb} by 0.5 in $t\bar{t}b\bar{b}$ $\sim$ 15% agreement with NLO $t\bar{t}b\bar{b}j$
- ✓ rescaling μ_{def} by 0.5 in $t\bar{t}b\bar{b}$ $\rightarrow$ within few % agreement with NLO $t\bar{t}b\bar{b}j$

benchmark with precision of $\sim 30\%$ to select optimal $t\bar{t}b\bar{b}$ scale

it motivates reduction of conventional $t\bar{t}b\bar{b}$ by a factor 2 (or more)

consistent with arguments based on reduction of inclusive $t\bar{t}b\bar{b}$ K-factor

Summary

- $t\bar{t}H(H \to b\bar{b})$ searches limited by theoretical uncertainty on $t\bar{t} + b$-jets background

- crucial to understand sizeable discrepancies between NLOPS $t\bar{t}b\bar{b}$ MC on the market
  - most notably in the spectrum of extra light-jet radiation
  - related to large $t\bar{t}b\bar{b}$ NLO K-factor

- We have shown that the scale dependence of $\sigma_{t\bar{t}b\bar{b}}$ and its interplay with the m_t/m_b mass gap support a reduced μ_R choice, which would:
  - yield a smaller K-factor and a smaller scale uncertainty
  - probably mitigate NLOPS discrepancies

- We have presented NLO predictions for $pp \to t\bar{t}b\bar{b}j$
  - first application of `OpenLoops2` (with `SHERPA`)
  - provides additional support for using a reduced μ_R choice in $pp \to t\bar{t}b\bar{b}$
  - should help reducing NLOPS uncertainties (by discarding less accurate MC predictions for light-jet spectrum)