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

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in collaboration with

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Outline

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

- Large NLO K-factor in $pp \to t\bar{t}b\bar{b}$ and scale choices

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

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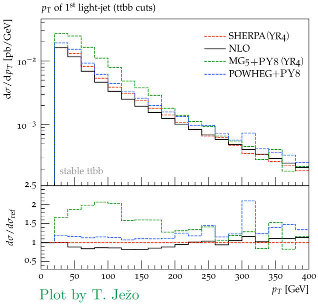
Discrepancies in $t\bar{t}b\bar{b}$ NLOPS generators

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

hypothesis on origin of NLOPS differences: interplay between PS and **large NLO $t\bar{t}b\bar{b}$ K-factor** which enters the PS matching in the soft regime

(1) origin of large K-factor to be understood

(2) **Idea**: improve theory accuracy constraining the NLOPS predictions by means of a benchmark $p_{T,j}$ spectrum with uncertainty well below 100%

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

This talk

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- ▷ Large NLO K-factor in $pp \to t\bar{t}b\bar{b}$ and scale choices

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

Large $t\bar{t}b\bar{b}$ NLO K-factor

Input parameters, PDFs and scale choices

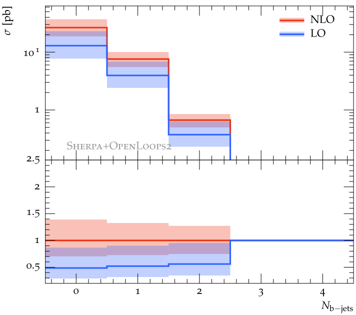
$$m_b = 4.75 \text{ GeV} \qquad m_t = 172.5 \text{ GeV}$$

$$\mu_\mathrm{R} = \sqrt{\mu_{t\bar{t}}\mu_{b\bar{b}}} \quad \text{with} \quad \mu_{b\bar{b}} = \sqrt{E_{T,b}E_{T,\bar{b}}} \quad \mu_{t\bar{t}} = \sqrt{E_{T,t}E_{T,\bar{t}}} \qquad \mu_\mathrm{F} = \frac{H_\mathrm{T}}{2} = \frac{1}{2}\sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i}$$

NLO PDFs used throughout, both at LO and NLO: `NNPDF_nlo_as_0118_nf_4` with $\alpha_s^{4\mathrm{f}}$

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

Inclusive b-jet multiplicity distribution



K-factor

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

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

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

Large $t\bar{t}b\bar{b}$ NLO K-factor

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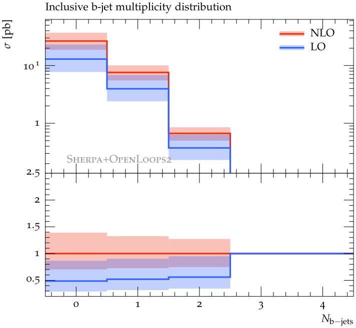
The NLO QCD cross sections for $pp \to t\bar{t}b\bar{b}$ feature a large K-factor

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



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Hypotheses on origin of large K-factor

Hypothesis A: sizeable NLO real emission contribution

- **large mass gap** in $t\bar{t}$ and $b\bar{b}$ systems: $m_b \ll m_t$
- $g \to b\bar{b}$ splittings at relatively soft scales: $Q_{b\bar{b}} \ll m_t$
- abudant NLO radiation with large $p_{T,j}$: $m_b < Q_{b\bar{b}} < p_{T,j} < m_t$

  $\Rightarrow \sigma_{NLO}$ strongly enhanced by hard jet radiation interpreted as $t\bar{t}gg(g \to b\bar{b})$

it enters as a "new process" described at LO ⇒ potentially large NLO QCD corrections

A: mass effects on $pp \to t\bar{t}b\bar{b}$ X-sections

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

Idea: study the NLO K-factor for different masses m_b, m_t: restrict the gap $m_b < p_{T,b} < Q_{b\bar{b}} < m_t$

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:

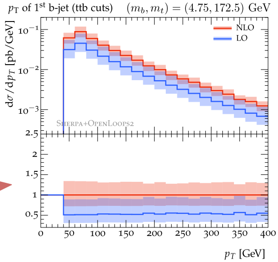
$$\mu_{\mathrm{R}} = \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$$

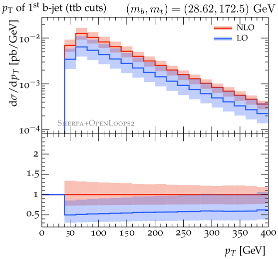
$$\mu_{\mathrm{F}} = \frac{H_T}{2}$$

× Large K-factor stable wrt variations of m_t, m_b gap

✓ good shapes in distributions

⇒ **hypothesis A disfavoured**





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$\Rightarrow \sigma_{NLO}$ strongly enhanced by hard jet radiation interpreted as $t\bar{t}gg(g \to b\bar{b})$

it enters as a "new process" described at LO $\Rightarrow$ potentially large NLO QCD corrections

Hypothesis B: non-optimal scales choices

- an improved μ_{R} choice might reduce the K-factor and also mitigate the NLOPS discrepancies

B: renormalisation scale choice

Natural μ_{R} scale choice for inclusive $\sigma_{\mathbf{t\bar{t}b\bar{b}}}$

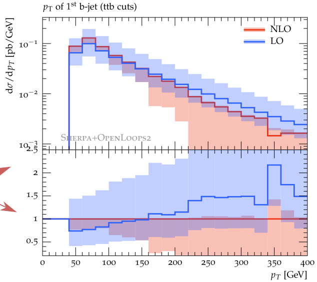
- ▹ if no mass gap i.e. $m_b = m_t$, the natural choice is $\mu_{\mathrm{R}} = m_t$
- ▹ the direct generalisation is $\mu_{\mathrm{R}} = \sqrt{m_b m_t} \sim 28.6$ GeV

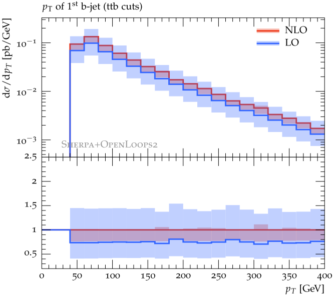
✓ reduced K-factor in the physical case ~ 1.14

✓ moderate $K-$factor for various m_b, m_t

× enhanced shape distortion in distributions

× unreliable scale uncertainties





motivates a reduced dynamic $\mu_{\mathrm{R}} = \xi \prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}^{1/4}$

Example: $\xi = 1/3$

✓ reduced K-factor

✓ no shape distortions in distributions

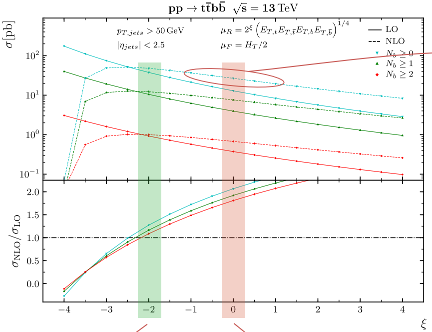
✓ $\sim 20\%$ scale uncertainties

B: renormalisation scale dependence

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

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

Average value $< \mu_\mathrm{R,def} >$: $N_{b\geq 0} \sim 73$ GeV $N_{b\geq 1} \sim 93$ GeV $N_{b\geq 2} \sim 124$ GeV



K-factor ~ 1

default

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

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

similar K-factor for different b-jets multiplicities

a factor $\xi = 2-4$ reduction of $\mu_\mathrm{R,def}$ brings

- $\mu_R/\xi \sim \sqrt{m_t m_b} = 28.6$ GeV
- **K-factor close to 1**
- scale uncertainty $\lesssim 20\%$

it supports hypothesis B

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

First jet emission from matrix element ⇒ accurate benchmark for p_T of light jet radiation

Idea: look at $p_{T,j}$ spectrum in $t\bar{t}b\bar{b}$ and validate against NLO prediction from $t\bar{t}b\bar{b}j$

- clarify discrepancies in the MCs
- particularly important when hard QCD radiation is relevant
- validate consistency of reduced μ_{R} for $t\bar{t}b\bar{b}$

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`

$$\Delta R = 0.4, \quad p_T > 50 \text{ GeV}, \quad |\eta| < 2.5$$

▷ input parameters and PDFs as in $t\bar{t}b\bar{b}$

All results shown have been obtained through `SHERPA-2.2.4` + `OpenLoops2`

$pp \to t\bar{t}b\bar{b}j$ K-factor and μ_R dependence

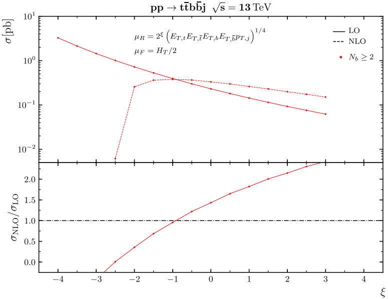
Improved choice of μ_{R} for $t\bar{t}b\bar{b}j$ which takes in consideration the jet kinematics

$$\mu^*_{\mathrm{R,def}} \equiv (E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}}\,p_{T,j})^{1/5}$$

	$\sigma_{N_{b\text{-jets}\geq 1}}$ [pb]			$\sigma_{N_{b\text{-jets}\geq 2}}$ [pb]		
Process	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$
$t\bar{t}b\bar{b}$, $\mu_{\mathrm{R,def}}$	$3.955^{+73\%}_{-39\%}$	$7.593^{+32\%}_{-27\%}$	1.92	$0.374^{+69\%}_{-38\%}$	$0.669^{+27\%}_{-25\%}$	1.79
$t\bar{t}b\bar{b}j$, $\mu^*_{\mathrm{R,def}}$	$2.165^{+96\%}_{-45\%}$	$3.340^{+19\%}_{-27\%}$	1.54	$0.232^{+92\%}_{-45\%}$	$0.333^{+14\%}_{-24\%}$	1.44

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

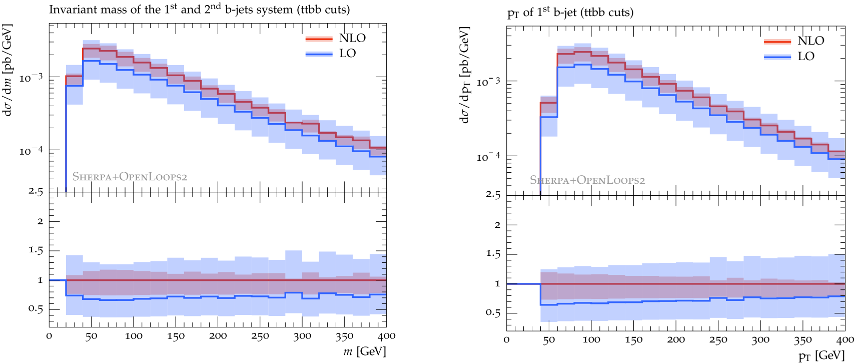
envelope of 7 points variation of μ_F and μ_R



- scale variation uncertainty significantly reduced at NLO
- factor 2 variations of only $\mu_R \sim +13\%$ and -23% scale uncertainty
- $K-$factor smaller wrt $t\bar{t}b\bar{b}$ at central value of μ_R $\Rightarrow$ no need to reduce $\mu^*_{\mathrm{R,def}}$

Distributions for $N_b \geq 2$ and $N_j \geq 1$

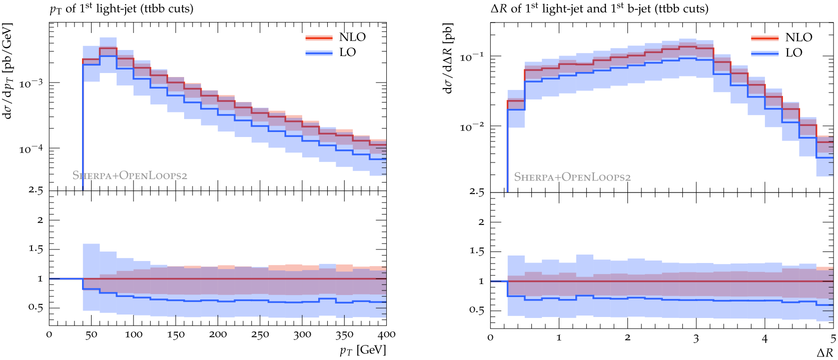
$$\mu^{*}_{\mathrm{R,def}} \equiv (E_{T,t} E_{T,\bar{t}} E_{T,b} E_{T,\bar{b}}\, p_{T,j})^{1/5}$$



- inclusive K-factor ~ 1.4
- shape of distributions remarkably stable wrt NLO corrections
- significant reduction of scale uncertainty at NLO $\Rightarrow$ below 20% over all spectrum

Light-jet observables at NLO

$\mu^*_{\mathrm{R,def}} \equiv (E_{T,t} E_{T,\bar{t}} E_{T,b} E_{T,\bar{b}}\, p_{T,j})^{1/5}$



- shape and normalisation of jet-p_T spectrum stable, in particular for $p_T \gtrsim 100$ GeV
- also other light-jet observables feature a stable NLO K-factor
- factor 2 variations of μ_{R} and μ_{F} give $\sim 25\%$ scale uncertainty over the whole spectrum

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

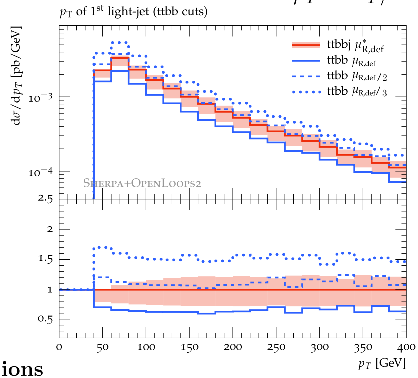
NLO $t\bar{t}b\bar{b}j$ benchmark for $\mathrm{d}\sigma/\mathrm{d}p_{T,j}$: **validation** and **tuning** of $t\bar{t}b\bar{b}$ prediction

i) envelope of 7-points NLO scale variation bands for $t\bar{t}b\bar{b}j$

ii) compared against prediction from $t\bar{t}b\bar{b}$ with nominal and rescaled $\mu_{\mathrm{R,def}}$

- ✓ remarkably good shape agreement over all the p_T spectrum
- ✓ no significant shape corrections (independently of μ_R rescaling!)
- ✓ rescaling $\mu_{\mathrm{R,def}}$ by 0.5 in $t\bar{t}b\bar{b}$ → $\sim$ 15% agreement with NLO $t\bar{t}b\bar{b}j$

$\mu_F = H_T/2$



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

⇒ **no room for** sizeable **NLOPS shape distortions**

Summary

- 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
  - possibly 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)