Theory progress on $t\bar{t}H(b\bar{b})$ background

Stefano Pozzorini

based on work with

T. Jezo, J. Lindert [arXiv:1802.00426]

F. Buccioni, M. Zoller [in preparation]

and HXSWG studies in collaboration with

F. Siegert, M. V. Garzelli, T. Jezo, J. Krause, A. Kardos, J. Lindert,
R. Podskubka, C. Reuschle, M. Zaro

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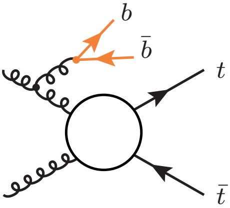
Foreword



Dominant $t\bar{t}H$ theory systematics from $t\bar{t}+b$-jet background to $t\bar{t}H(b\bar{b})$

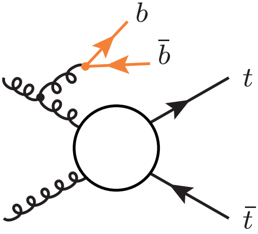
- can be constrained from $t\bar{t}+b$-jet data but "extrapolation" to signal region requires $t\bar{t}+b$-jet shapes with theory precision better than 10%
- extensive studies within $t\bar{t}H$ HXSWG
- interplay with top community (MC experts, $t\bar{t}b\bar{b}$ measurements, ...) important

Outline

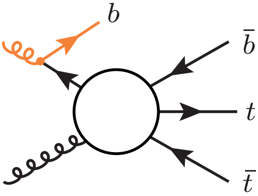
1. Different $t\bar{t}+b$-jet simulation approaches
2. New Powheg+OpenLoops $t\bar{t}b\bar{b}$ generator
3. Ongoing NLOPS $t\bar{t}b\bar{b}$ studies within HXSWG
4. $t\bar{t}b\bar{b}$+ jet at NLO

Option 1: inclusive NLOPS $t\bar{t}$ 5F (e.g. Powheg)

$t\bar{t}b\bar{b}$ described through $t\bar{t}j$ tree MEs plus $g \to b\bar{b}$ shower splittings



$gg \to t\bar{t}g$ + FS splittings



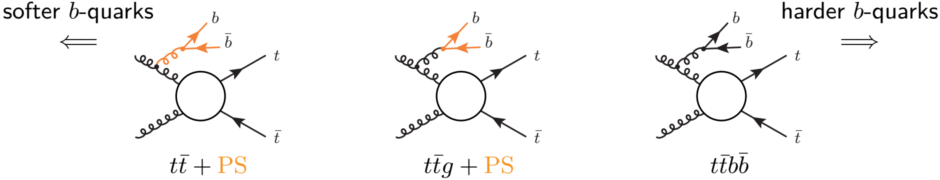
$\bar{b}g \to t\bar{t}\bar{b}$ + IS splittings

Precision vs accuracy

- precision lower than LO but parton shower allows for accurate tuning to data
- residual uncertainties difficult to quantify

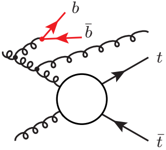
improved description based on $t\bar{t}b\bar{b}$ MEs preferable

Option 2: (N)LO merging $t\bar{t}+0,1,2$ jets 5F

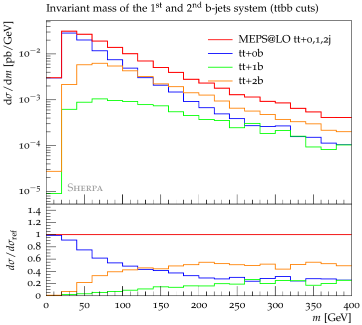


$t\bar{t}b\bar{b}$ described through $t\bar{t}+0,1,2$ jet MEs and $g\to b\bar{b}$ shower splittings

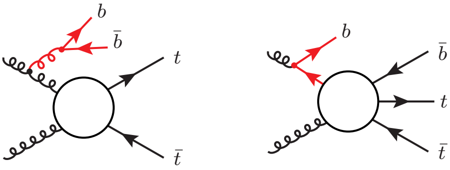
- k_T-resolution cut separates MEs (with $m_b=0$) from shower (collinear approx.)
- $g\to b\bar{b}$ splittings dominated by parton shower up to $m_{b\bar{b}}\gtrsim$ 100 GeV due to competition with harder light jets [arXiv:1802.00426]



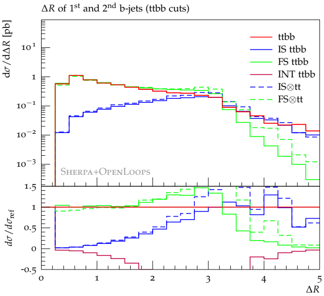
m_{bb} with ttbb cuts



Option 3: NLOPS $t\bar{t}b\bar{b}$ in 4F scheme



ΔR_{bb} with ttbb cuts



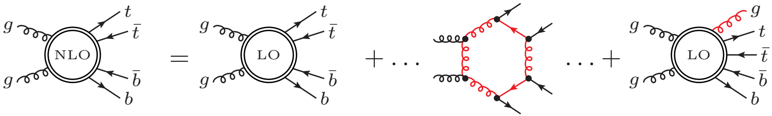
4F $pp \to t\bar{t}b\bar{b}$ MEs with $m_b > 0$ at NLOPS

- MEs cover full b-quark phase space including IS and FS $g \to b\bar{b}$ collinear splittings

⇒ NLOPS accuracy for $t\bar{t} + 2\,b$-jet and $t\bar{t} + 1\,b$-jet observables! [Cascioli et al '13]

Arguments in support of 4F scheme (see backup slides)

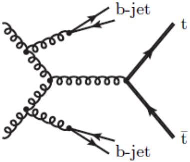
- dominance of final-state $g \to b\bar{b}$ splittings [arXiv:1802.00426]
- negligible $g \to b\bar{b}$ framentation logs beyond NLO at $p_T \lesssim$ 50–100 GeV [Mangano, Nason 1992]



Important features of $pp \to t\bar{t}b\bar{b}$ at NLO

- multiple scales from 5 to 500 GeV (gap between $b\bar{b}$ and $t\bar{t}$ systems)
- default scale choice: $\mu_F = H_T/2$ and $\mu_{\mathrm{R,def}} = \left(E_{T,t}E_{T,\bar{t}}\,E_{T,b}E_{T,\bar{b}}\right)^{1/4}$
- 70–80% LO uncertainty from $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R)$ reduced to 20–30% at NLO [Bredenstein et al. '09–'10; Bevilacqua et al. '10]

Nontrivial NLOPS issues



- in Higgs region up to 30% matching/shower effects from double $g \to b\bar{b}$ splittings [Cascioli et al '13]
- crucial to understand $g \to b\bar{b}$ splittings and matching+shower uncertainties
- can exploit variety of $t\bar{t}b\bar{b}$ NLO generators (see later)

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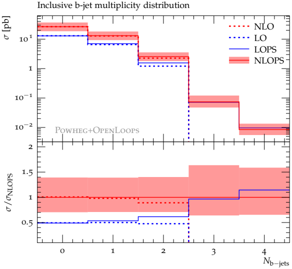
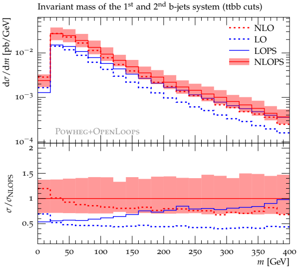
$t\bar{t}b\bar{b}$ 4F with Powheg+PY8 [Jezo, Lindert, Moretti, S.P 1802.00426]

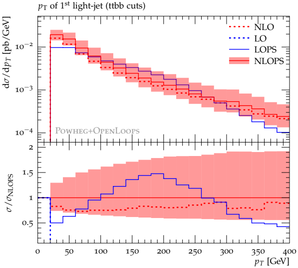
N_b



$M_{b_1 b_2}$



p_{T,j_1}



Moderate NLOPS/NLO corrections

- consistent with NLO scale-variation bands
- 20–30% at $m_{bb} \sim 100\,\mathrm{GeV}$ (confirms double splittings)

Light-jet p_T

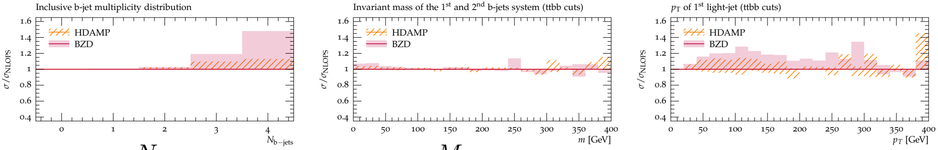
- shape of LO+PY8 very different from NLO (see $p_T \sim 200\,\mathrm{GeV}$)
- no effect on Powheg+PY8 spectrum (very close to NLO)

Matching+shower uncertainties of Powheg $t\bar{t}b\bar{b}$ [1802.00426] I

Stability of Powheg

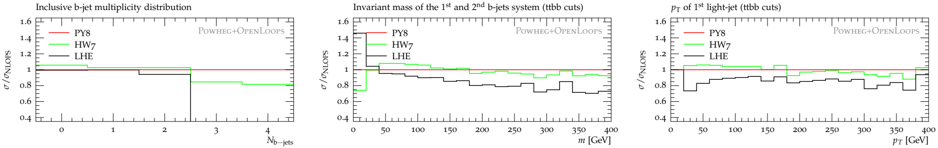
- thanks to shower-free 1^{st} emission and "bornzerodamp mechanism" (see backup)

Dependence on matching scales ($h_{\mathrm{damp}} = H_T/4, H_T/2, H_T, 1.5m_t$ and $h_{\mathrm{bzd}} = 2, 5, 10$)



N_b $\qquad M_{b_1 b_2}$ $\qquad p_{T,j_1}$

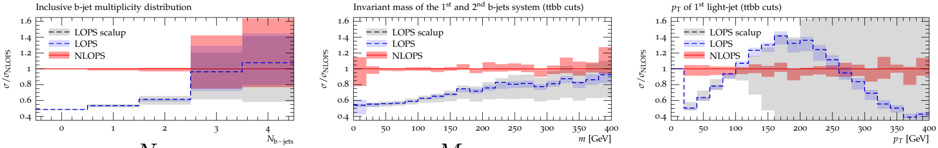
Powheg+PY8 vs Herwig7



- MC uncertainties << QCD scale dependence: **percent level** for inclusive $t\bar{t} + b$-jet observables and 10–20% level in jet-p_T spectrum

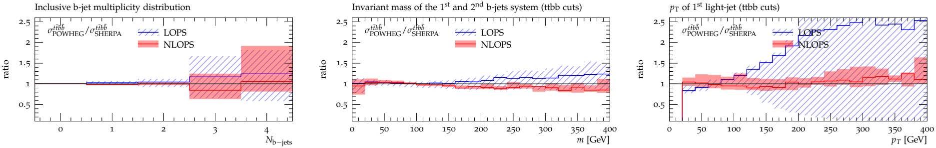
Matching+shower uncertainties of Powheg $t\bar{t}b\bar{b}$ [1802.00426] II

Variations of $g \to b\bar{b}$ splittings + choice of α_S + scalup in PY8



N_b $M_{b_1 b_2}$ p_{T,j_1}

$t\bar{t}b\bar{b}$ Powheg+PY8 vs Sherpa (only Powheg matching+shower uncertainties)



- double-splitting effects stable wrt variations of $g \to b\bar{b}$ in PY8
- less than 10% NLOPS difference using different showers and matching methods*

*slightly more significant differences using Sherpa 2.2 recoil scheme

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Ongoing NLOPS $t\bar{t}b\bar{b}$ studies within HXSWG

Tool	MC@NLO	Powheg	Pythia	Herwig	Sherpa	MC contacts
SHERPA2.2+OPENLOOPS	x				x	F. Siegert, J. Krause
MG5_AMC@NLO	x		x	x		M. Zaro
MATCHBOX+OPENLOOPS	x			x		C. Reuschle, R. Posdkubka
POWHEG+HELAC		x	x	x		M.V. Garzelli, A. Kardos
POWHEGBOX+OPENLOOPS		x	x	x		T. Jezo, J. Lindert
	3	2	3	4	1	

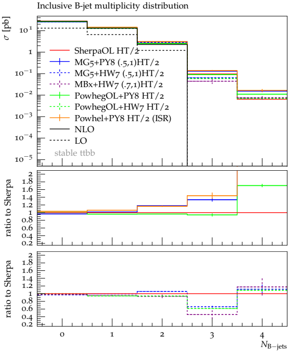
Rich variety of predictions

- 5 MC tools, 2 matching methods, 3 showers

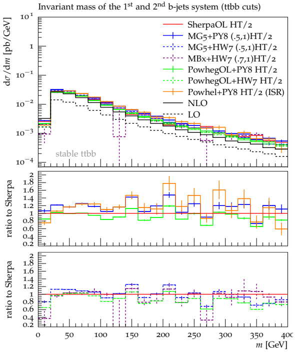
⇒ goal is to disentangle and quantify all sources of TH uncertainty

Comparison of observables with $N_b \geq 2$

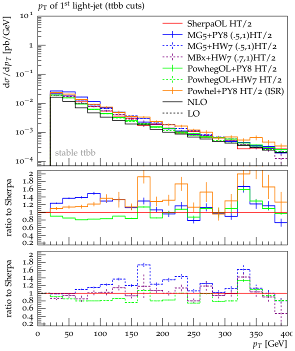
N_b



$M_{b_1 b_2}$



p_{T,j_1}



NLO+Herwig tools vs Sherpa (2nd ratio)

- all predictions in quite good agreement

NLO+PY8 tools vs Sherpa (1st ratio)

- Powheg+OpenLoops ≃ Sherpa while MG5+PY8 ≃ Powhel+PY8* 20–50% higher

*does not implement h_{damp} restriction of FSR

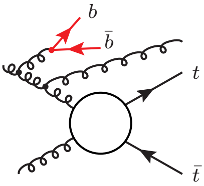
Current interpretation of leading MC differences

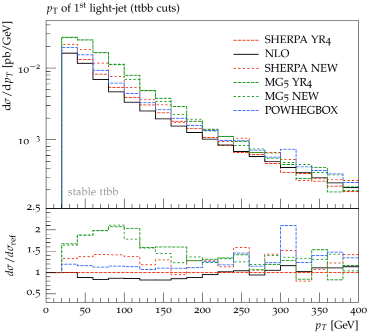
Large $t\bar{t}b\bar{b}$ K-factor in matching of NLO radiation spectrum

$$\frac{\bar{B}_{\mathrm{soft}}}{B} \sim \frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}} \sim 2 \quad \Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B \mathrm{d}\Phi_1} = \underbrace{R}_{\mathrm{ME}} + \underbrace{R_{\mathrm{soft}}}_{\mathrm{shower}} \times \underbrace{\left[\frac{\bar{B}_{\mathrm{soft}}}{B}\Delta - 1\right]}_{\gtrsim 100\% \text{ instead of } \mathcal{O}(\alpha_S)}$$

Distorts jet-p_T spectrum by 100%

$\Rightarrow$ sizeable effects from hard-jet recoil on soft b-jets (e.g. N_b-bin migrations)





Questions: why $\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} \sim 2$? Can we reduce it?

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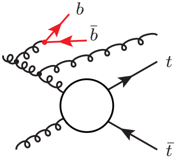
Origin of large $t\bar{t}b\bar{b}$ K-factor [F. Buccioni, S.P., M. Zoller]

Hypothesis A: real emission



- $g \to b\bar{b}$ splittings at rather soft scales $Q_{b\bar{b}} \ll m_t$
- abundant NLO radiation with hard p_T: $m_b < Q_{b\bar{b}} < p_T < m_t$
- due to large mass gap $m_t/m_b \simeq 36$

Test of hypothesis A

- check if K factor decreases when reducing m_t/m_b (using default μ_R, μ_F)

$m_b\,[\mathrm{GeV}]]$	4.75	28.6	172.5
$K(N_b \geq 0)$	2.06	1.90	1.82
$K(N_b \geq 1)$	1.92	1.86	1.81
$K(N_b \geq 2)$	1.79	1.78	1.79

- $N_b \geq 0, 1, 2$ cross sections $\mathcal{O}\left(10^{-3}\right)$ suppressed when $m_t/m_b \to 1$
- but $K \sim 2$ independently of m_t/m_b $\Rightarrow$ hypothesis A not confirmed

Origin of large $t\bar{t}b\bar{b}$ K-factor

Hypothesis B: scale choice

- $\sigma_{\mathrm{LO}} \sim \alpha_S^4(\mu_R)$ strongly sensitive to $\mu_R \Rightarrow K = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} \gg 1$ can be due to suboptimal μ_R choice
- moderate redefinition of μ_R can guarantee $K \sim 1$ but convergence improvement beyond NLO not guaranteed w.o. additional arguments.

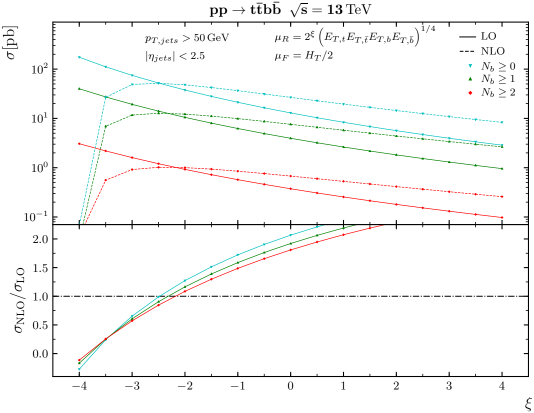
Natural scale choice for inclusive $\sigma_{t\bar{t}b\bar{b}}$

- for $m_b = m_t$ the natural choice is $\mu_R = m_t$
- natural generalisation $\mu_R = \sqrt{m_b m_t} \Rightarrow$ good convergence for $1 \leq m_t/m_b \leq 36$

$m_b\,[\mathrm{GeV}]$	4.75	15.7	52.1	172.5
$\sqrt{m_b m_t}\,[\mathrm{GeV}]$	28.7	52.1	94.8	172.5
$K(N_b \geq 0)$	1.14	1.24	1.32	1.35

$\Rightarrow$ $\langle \mu_{R,\mathrm{def}} \rangle \simeq 66\,\mathrm{GeV}$ should be reduced by factor 2–3 to match $\sqrt{m_b m_t} = 28.7\,\mathrm{GeV}$

Improving convergence by reducing $\mu_{R,\mathrm{def}}$



Rescaling $\mu_R \to \mu_{R,\mathrm{def}}/3$ with fixed $\mu_F = H_T/2$ yields

- reduced K-factor and scale dependence for $N_b \geq 0, 1, 2$ ($K \sim 1.3$ for $N_b \geq 2$)
- $\sim 60\%$ higher σ_{NLO} ⇒ more consistent with data

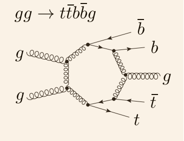
$t\bar{t}b\bar{b}+j$ NLO calculation [F. Buccioni, S.P., M. Zoller]

Idea

- real emission contribution to $t\bar{t}b\bar{b}$ at NNLO
- especially useful if hard QCD radiation important
- precise prediction for light-jet p_T spectrum can be used to
  - ⇒ clarify MC discrepancies
  - ⇒ test consistency of reduced $\mu_{R,\mathrm{def}}$ in $t\bar{t}b\bar{b}$ at NLO

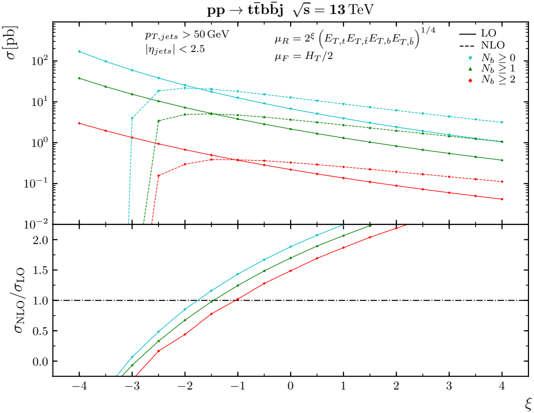
Challenging $2 \to 5$ calculation with Sherpa+OpenLoops2

- 25×10^3 loop diagrams with $2^7 = 128$ helicity states
- factor 3 speed-up with on-the-fly reduction [Buccioni, S.P.,Zoller]



$t\bar{t}b\bar{b}j$ K-factor and scale dependence (PRELIMINARY)

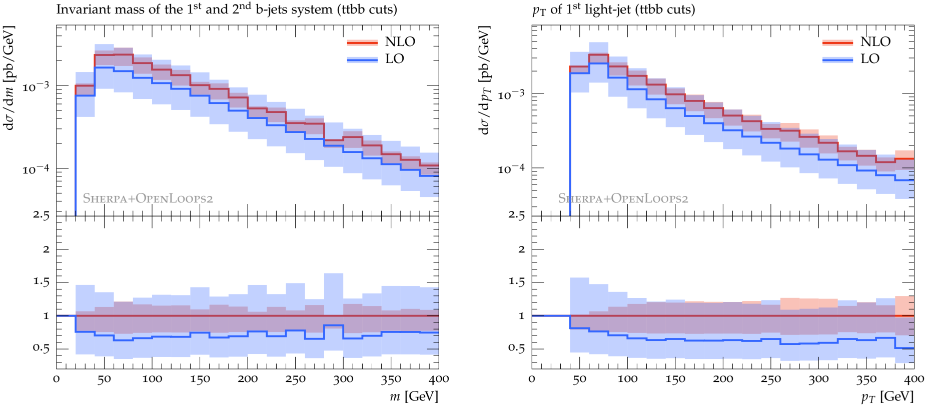
$N_b \geq 0, 1, 2$ **b-jets +** $N_j \geq 1$ **light-jet** with $|\eta| < 2.5$ and $p_T > 50\,\mathrm{GeV}$



- decent convergence at $\mu_R = \mu_{R,\mathrm{def}}$ and $\mu_F = H_T/2$
- in the following: improved using $\mu_R = \mu^*_{\mathrm{R,def}} = \left(E_{T,t}E_{T,\bar{t}}\,E_{T,b}E_{T,\bar{b}}\,p_{T,j}\right)^{1/5}$

$\Rightarrow$ $K = 1.44$ and $\sim 20\%$ scale uncertainty for $N_b \geq 2$

Distributions for $N_b \geq 2$, $N_j \geq 1$ (PRELIMINARY)



⇒ shapes of $t\bar{t}b\bar{b}$ and extra-jet distributions quite stable wrt NLO corrections and scale variations

⇒ shape and normalisation of jet-p_T spectrum with 25% or less scale uncertainty above 100 GeV

$t\bar{t}b\bar{b}$ scale tuning using $t\bar{t}b\bar{b}j$ at NLO (PRELIMINARY)

NLO $t\bar{t}b\bar{b}j$ benchmark for $\mathrm{d}\sigma/\mathrm{d}p_{T,j}$: conservative envelope of bands around

$$\mu^*_{\mathrm{R,def}} = \left(E_{T,t}E_{T,\bar{t}}\,E_{T,b}E_{T,\bar{b}}\,p_{T,j}\right)^{1/5} \quad \text{and} \quad \mu^*_{\mathrm{R,mbb}} = \left(E_{T,t}E_{T,\bar{t}}\,E_{T,b\bar{b}}m_{b\bar{b}}\,p_{T,j}\right)^{1/5}$$

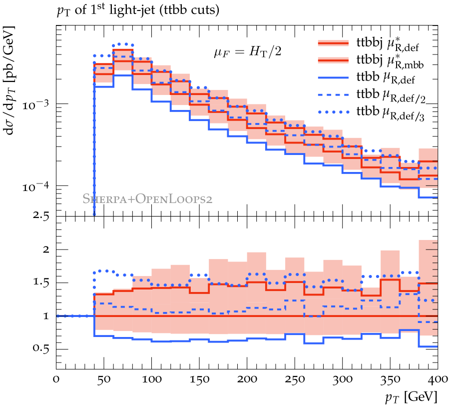
Tuning of NLO $t\bar{t}b\bar{b}$ prediction

- optimal normalisation reducing $\mu_{R,\mathrm{def}}$ by factor 2–3

⇒ consistent with previous arguments!

- no significant shape corrections (independently of μ_R rescaling!)

⇒ no room for sizeable NLOPS shape distortions



Conclusions and Outlook

Variety of NLOPS $t\bar{t}b\bar{b}$ generators (8 combinations of NLOPS methods $\otimes$ showers)

- excellent basis for $t\bar{t}+b$-jet theory predictions and uncertainties
- open issues with NLO matching ⇔ large K-factor, multiple scales in $t\bar{t}b\bar{b}$

3 independent TH arguments for improved $t\bar{t}b\bar{b}$ scale choice

⇒ should bring σ_{NLO} closer to $t\bar{t}b\bar{b}$ data

⇒ should reduce spread of MC predictions (ongoing studies)

Brand new calculation of $t\bar{t}b\bar{b}j$ at NLO

⇒ can be used to further constrain $t\bar{t}b\bar{b}$ generators

Good prospects to understand/reduce systematic uncertainty of $t\bar{t}H(b\bar{b})$ analyses

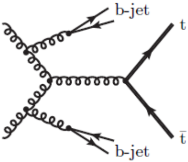
Backup slides

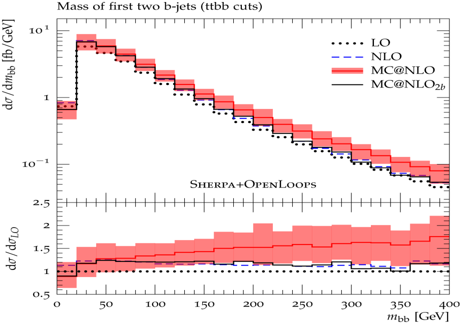
NLOPS $t\bar{t}b\bar{b}$ 4F with SHERPA+OPENLOOPS [Cascioli et al '13]

Convergence of 4F scheme but unexpected MC@NLO enhancement

	ttb	$ttbb$	$ttbb\,(m_{bb} > 100)$
$\sigma_{\rm LO}$[fb]	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
$\sigma_{\rm NLO}$[fb]	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
$\sigma_{\rm NLO}/\sigma_{\rm LO}$	1.25	1.21	1.15
$\sigma_{\rm MC@NLO}$[fb]	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181^{+20\%+8.1\%}_{-20\%-6.0\%}$
$\sigma_{\rm MC@NLO}/\sigma_{\rm NLO}$	1.01	1.07	1.28

Large enhancement (~30%) in Higgs region from double $g \to b\bar{b}$ splittings





One $g \to b\bar{b}$ splitting from PS

⇒ TH uncertainties related to matching, shower and 4F/5F schemes crucial!

Missing large logarithms from $g \to b\bar{b}$ fragmentation? I

Probability of $g \to b\bar{b}$ in a hard gluon jet [Mangano and Nason, PLB 285 (1992)]

$$\rho(Q^2, K^2) = \int_{2m_b}^{Q} \mathrm{d}K \, P_{g \to b\bar{b}}(K) \times n_g(Q^2, K^2)$$

$g \to b\bar{b}$ splitting probability at virtuality $K^2 = m_{b\bar{b}}^2$

$$P_{g \to b\bar{b}}(K) = \frac{\alpha_S(K^2)}{3\pi K} \left(1 + \frac{2m_b^2}{K^2}\right) \sqrt{1 - \frac{4m_b^2}{K^2}}$$

Multiplicity of gluons with virtuality K^2 in hard-gluon jet with $p_T = Q$

$$n_g(Q^2, K^2) = \left[\frac{\ln(Q^2/\Lambda^2)}{\ln(K^2/\Lambda^2)}\right]^a \cosh\left[\sqrt{\frac{2C_A}{\pi b}} \left(\sqrt{\ln(Q^2/\Lambda^2)} - \sqrt{\ln(K^2/\Lambda^2)}\right)\right]$$

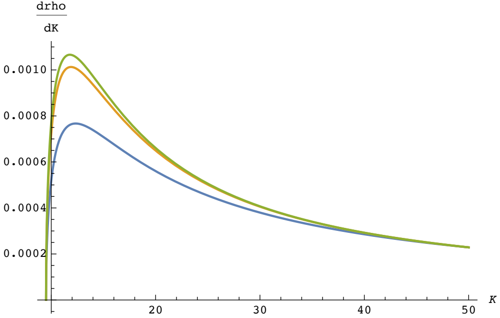
Perturbative expansion in $\alpha_S = \alpha_S(Q^2) = \left[b \ln(Q^2/\Lambda^2)\right]^{-1}$

$$\frac{\mathrm{d}\rho(Q^2, K^2)}{\mathrm{d}K} = \left.\frac{\mathrm{d}\rho(Q^2, K^2)}{\mathrm{d}K}\right|_{\mathrm{LO}} \times \left[1 + \alpha_S \left(C_1 L^2 + \ldots\right) + \alpha_S^2 \left(C_2 L^4 + \ldots\right) + \ldots\right]$$

with double logarithms $L = \ln(K^2/Q^2)$

Missing large logarithms from $g \to b\bar{b}$ fragmentation? II

Distribution $\mathrm{d}\rho(Q^2, K^2)/\mathrm{d}K$ at LO, NLO and NNLO for $Q = 50\,$GeV

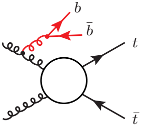


- higher-order effects well approximated by NLO
- peak close to threshold ($K \gtrsim 2m_b$) but long tail

Total $g \to b\bar{b}$ probability

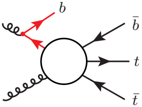
Q[GeV]	LO	NLO	NNLO	NLO/LO	NNLO/NLO
50	2.08%	2.44%	2.51%	1.17	1.03
100	2.73%	3.50%	3.71%	1.28	1.06
500	3.84%	6.06%	7.05%	1.59	1.16

$t\bar{t}b\bar{b}$ dominated by FS $g \to b\bar{b}$ splittings [1802.00426]



$t\bar{t}b\bar{b}$ topologies with FS $g \to b\bar{b}$ splittings

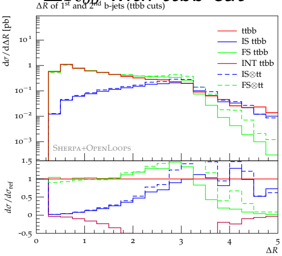
- dominant in full ttbb and ttb phase space
- notion of $g \to b\bar{b}$ splittings and IS/FS separation seems ill defined at large ΔR_{bb}, m_{bb}, $p_{T,b}$ due to sizable interferences



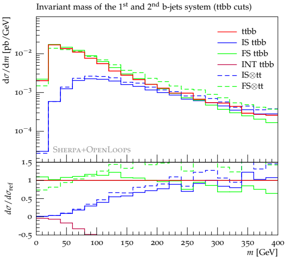
$t\bar{t}b\bar{b}$ topologies with IS $g \to b\bar{b}$ splittings

- mostly clearly subdominant (no need for 5F scheme resummation)

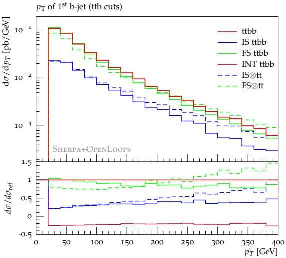
ΔR_{bb} with ttbb cut



m_{bb} with ttbb cuts



p_{T,b_1} with ttb cuts

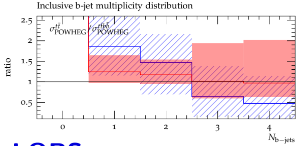


supports choice of 4F scheme with $m_b > 0$ and no b-quark PDF

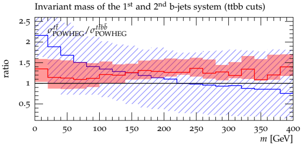
Powheg $t\bar{t}b\bar{b}$ vs Powheg $t\bar{t}$ inclusive [1802.00426]

Plotted bands: matching+shower (no QCD scale) uncertainties only for $t\bar{t}$ generator

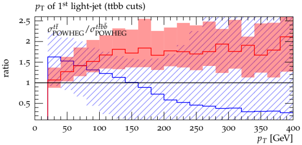
N_b



$M_{b_1b_2}$



p_{T,j_1}



LOPS

- uncertainties beyond factor 2
- large differences in N_b, m_{bb} and jet-p_T

NLOPS

- differences strongly reduced at NLOPS ("Powheg miracle")
- $t\bar{t}$ exceeds $t\bar{t}b\bar{b}$ by only $\sim 20\%$ in N_b and m_{bb} shape is OK (100% excess in the jet-p_{T} tail)

Motivation for $t\bar{t}b\bar{b}$ NLOPS lies in smaller (see previous plots) and better defined theory uncertainties

How to compare MC@NLO vs Powheg matching?

Splitting of NLO radiation into soft/hard parts

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B} = \underbrace{\left[B(\Phi_B) + V(\Phi_B) + \int \mathrm{d}\Phi_1 R_{\text{soft}}(\Phi_B, \Phi_1)\right]}_{=:\ \bar{B}_{\text{soft}}(\Phi_B)\ \supset \text{ integrated soft radiation}} \underbrace{\left[\Delta(t_{\text{IR}}) + \Delta(k_T)\frac{R_{\text{soft}}(\Phi_R)}{B(\Phi_B)}\,\mathrm{d}\Phi_1\right]}_{\text{resummation of soft radiation}}$$

$$+ \underbrace{\left[R(\Phi_R) - R_{\text{soft}}(\Phi_R)\right]\mathrm{d}\Phi_1}_{\text{remnant hard radiation}}$$

Powheg vs MC@NLO difference only in R_{soft}

Powheg: $R_{\text{soft}}(\Phi_R) = R(\Phi_R)\, g_{\text{soft}}(\Phi_1, h_{\text{damp}})$ matrix element

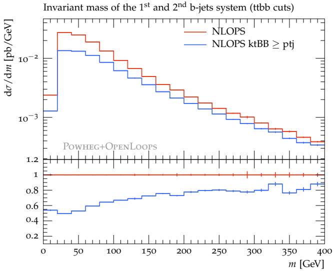
MC@NLO: $R_{\text{soft}}(\Phi_R) = B(\Phi_B) \otimes K_{\text{shower}}(\Phi_1)\, g_{\text{soft}}(\Phi_1, \mu_Q)$ parton shower

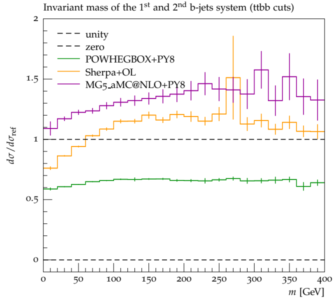
Soft profile $g_{\text{soft}}(\Phi_1, \mu)$ restricts R_{soft} to $k_T \lesssim \mu$ region

$\Rightarrow$ choose $h_{\text{damp}} = \mu_Q$ and g_{soft} as similar as possible for consistent comparison

NLOPS separation of soft/hard radiation

m_{bb}


Invariant mass of the 1st and 2nd b-jets system (ttbb cuts)


Invariant mass of the 1st and 2nd b-jets system (ttbb cuts)

Natural kinematic separation of $\sigma^{\rm NLO}_{t\bar{t}b\bar{b}}$

$$\frac{p_T(\text{jet})}{k_T(g \to b\bar{b})} \begin{cases} < 1 & \text{soft} \\ > 1 & \text{hard} \end{cases}$$

$\Rightarrow$ $\sim 50\%$ of $\sigma_{\rm NLO}$ soft/hard

Technical separation in NLOPS tools

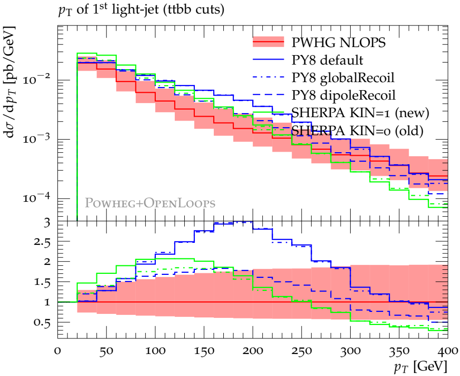
- in Powheg $\sim 50\%$ soft/hard (as a result of $h_{\rm bzd}$)
- in MC@NLO tools (especially MG5+PY8) soft contribution $\gtrsim 100\%$

MC uncertainties can be reduced by

- better understanding/careful treatment of large K-factor and hard radiation

Comparison of different showers and recoil schemes

p_{T,j_1}



LOPS with different showers and recoil schemes (overall NLO normalisation)

- large MC effects may be due to the recoil effects of QCD radiation on b-jets
- PY8 dipole recoil scheme more consistent with NLOPS radiation spectrum, hower not supported in MC@NLO matching
- also Sherpa (with old and new recoil schemes) more consistent with NLOPS

Setup for $t\bar{t}b\bar{b}$ 4F Powheg+OpenLoops predictions [arXiv:1802.00426]

Aspects identical to HXSWG YR4

- NNPDF30_NLO_as_0118_nf_4
- $\mu_R = (E_{T,t} E_{T,\bar{t}} E_{T,b} E_{T,\bar{b}})^{1/4}$
- $\mu_F = H_T/2$,
- $h_{damp} = H_T/2$,

Matching scale variations

- $h_{damp} = H_T/4, H_T/2, H_T, 1.5 m_t$
- $h_{bzd} = 2, 5, 10$

Shower and PDFs for showering

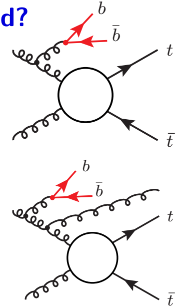
- A14 Pythia tune with $\alpha_S(M_Z) = 0.127$
- NNPDF2.3 LO 5F PDFs

NLOPS subtleties for multi-scale problems [1802.00426]

Matching based on factorisation of S-radiation wrt hard $t\bar{t}b\bar{b}$ process

$$R_{\text{soft}}(\Phi_R) \simeq B(\Phi_B) \otimes K_{\text{soft/coll}}(\Phi_{\text{rad}}) \qquad \text{for} \quad k_T < h_{\text{damp}} \sim m_t$$

What about radiation with $p_{T,b} < k_T < h_{\text{damp}}$? Soft or hard?



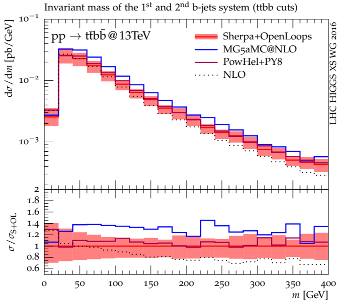
- $t\bar{t}b\bar{b}$ factorisation can fail and factorising hard $t\bar{t}$+jet subprocess can be more appropriate
- example: hard jet radiation in the direction of $b\bar{b}$ system
  - $\Phi_B \to \Phi_R$ FKS mappings $\Rightarrow$ $b\bar{b}$ system absorbs jet recoil and becomes much softer
  - $R(\Phi_R)$ enhancement that violates $ttbb$ factorisation
- similar issues expected also in MC@NLO matching

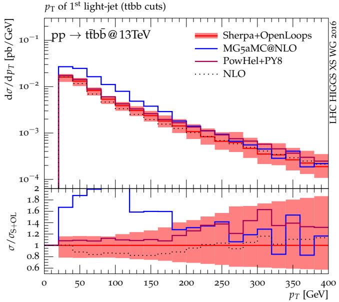
Powheg "safety" system: resummation only if $R_{\text{soft}} < h_{\text{bzd}} \times B \otimes K_{\text{soft/coll}}$

$$g_{\text{soft}}(\Phi_{\text{rad}}, h_{\text{damp}}, h_{\text{bzd}}) = \frac{h_{\text{damp}}^2}{h_{\text{damp}}^2 + k_T^2}\, \theta\Big(h_{\text{bzd}} B(\Phi_B) \otimes K_{\text{soft/coll}}(\Phi_{\text{rad}}) - R(\Phi_R)\Big)$$

$\Rightarrow$ high stability wrt h_{damp} variations

YR4 comparisons of NLOPS $t\bar{t}b\bar{b}$ generators [1610.07922]


Invariant mass of the 1st and 2nd b-jets system (ttbb cuts)


p_T of 1st light-jet (ttbb cuts)

MG5aMC@NLO+PY8 (4F) vs Sherpa (4F)

- 40% NLOPS/NLO enhancement of $t\bar{t} + 2b$ XS in MG5
- related to sizeable enhancement of NLO radiation at $p_T \sim 100\,\text{GeV}$
- sensitive to resummation scale (scalup) in MG5

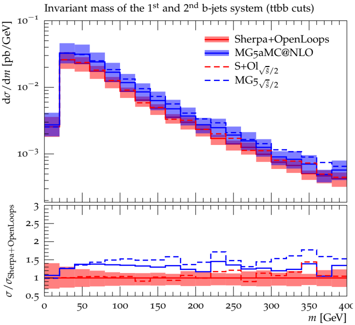
Question: large uncertainty or not?!

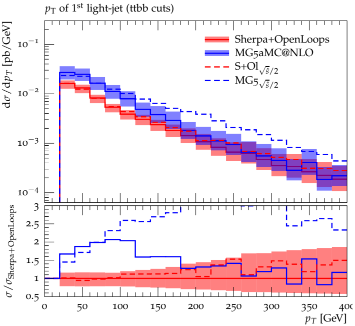
PowHel+PY8 (5F) vs Sherpa (4F)

- much better agreement
- but 5F scheme in Powhel not appropriate for collinear $g \to b\bar{b}$ splittings (ad-hoc cuts)

Question: small theory uncertainty or accidental?

Dependence on resummation scale μ_Q (shortly after YR4)





Nominal MG5_aMC and Sherpa+OpenLoops predictions in YR4

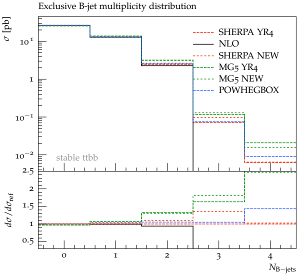
- MG5_aMC supports only* $\mu_Q = f(\xi)\sqrt{\hat{s}} \Rightarrow$ smearing function restricted to $0.1 < f(\xi) < 0.25$ to mimic recommended $\mu_Q = H_T/2$ implemented in Sherpa

μ_Q variations enhance the discrepancy

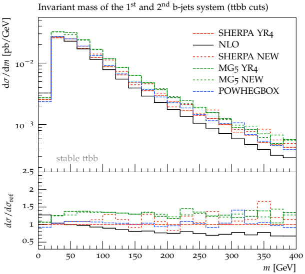
- $\mu_Q = \sqrt{\hat{s}}/2$ in Sherpa to mimic MG5_aMC default choice $0.1 < f(\xi) < 1$
- strong μ_Q-sensitivity of MG5_aMC $\Rightarrow$ much more pronounced deviations

Changes in Sherpa and MG5 wrt YR4 [1610.07922]

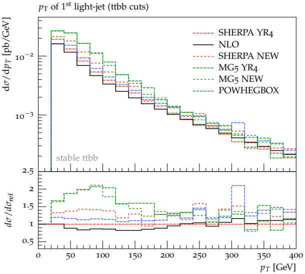
N_b



m_{bb}



p_{T,j_1}



Bottom line

- MG5+PY8 did not change significantly (in spite of $\hat{s} \to H_T$ based scalup)
- Sherpa moved in the direction of MG5+PY8
  - $+35\%$ in the jet-p_T spectrum (but little impact on inclusive shapes)
  - due to new default recoil scheme (for 2nd and higher emissions)
  - and other changes (to be clarified in detail)

Interplay of $K \gg 1$ and negative σ_H in MC@NLO

$$\frac{d\sigma}{d\Phi_B} = \underbrace{\bar{B}_{\mathrm{soft}}(\Phi_B)\left[\Delta(t_{\mathrm{IR}}) + \Delta(k_T)\mathcal{K}_{\mathrm{soft}}(\Phi_1)\,d\Phi_1\right]}_{\mathrm{S-events\ (LHE\times shower)}} + \underbrace{\Big[R(\Phi_R) - B(\Phi_B)\mathcal{K}_{\mathrm{soft}}(\Phi_1)\Big]d\Phi_1}_{\mathrm{H-events}}$$

Soft radiation approximated by paron shower in the soft region $k_T \lesssim \mu_Q$

$$R(\Phi_R) \longrightarrow B(\Phi)\mathcal{K}_{\mathrm{soft}}(\Phi_1) = B(\Phi)K_{\mathrm{shower}}(\Phi_1)\,g_{\mathrm{soft}}(\Phi_1,\mu_Q)$$

and integrated out in

$$\bar{B}_{\mathrm{soft}}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + B(\Phi_B)\int d\Phi_1\mathcal{K}_{\mathrm{soft}}(\Phi_1)$$

Matching distorted by K-factor $\bar{B}_{\mathrm{soft}}/B \gtrsim 2$ and $\underbrace{(R - B\mathcal{K}_{\mathrm{soft}})}_{H-\mathrm{weight}} < 0$

$$\frac{d\sigma}{d\Phi_B d\Phi_1} = R + \underbrace{\left[\frac{\bar{B}_{\mathrm{soft}}}{B}\Delta - 1\right]}_{\gtrsim\ 100\%\mathrm{distortion}} B\mathcal{K}_{\mathrm{soft}} = \underbrace{\left(\frac{\bar{B}_{\mathrm{soft}}}{B}\Delta\right)R}_{\mathrm{max\ resummation}} + \underbrace{\left[\frac{\bar{B}_{\mathrm{soft}}}{B}\Delta - 1\right]}_{\gtrsim\ 100\%}\underbrace{(B\mathcal{K}_{\mathrm{soft}} - R)}_{>0}$$

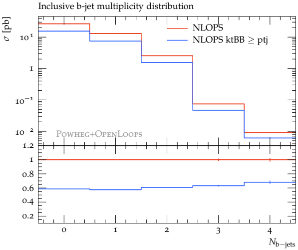
⇒ strongly enhanced positive correction beyond “max resummation”: unphysical?

Natural separation approach

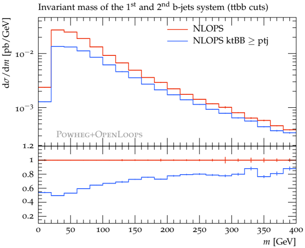
Compare hardness of $g \to b\bar{b}$ splitting to p_T of NLO radiation

- $p_T(\text{jet}) < k_T(g \to b\bar{b}) \quad \Rightarrow \quad$ soft
- $p_T(\text{jet}) > k_T(g \to b\bar{b}) \quad \Rightarrow \quad$ hard

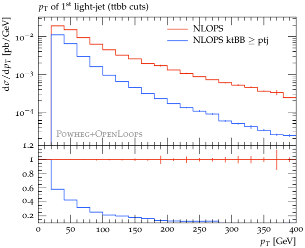
N_b


Inclusive b-jet multiplicity distribution

m_{bb}


Invariant mass of the 1st and 2nd b-jets system (ttbb cuts)

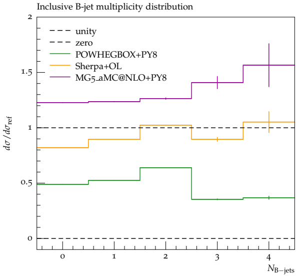
p_{T,j_1}


p_T of 1st light-jet (ttbb cuts)

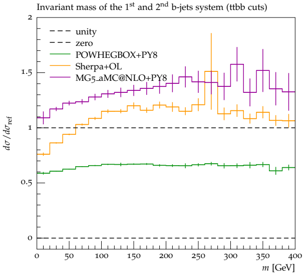
- roughly 1/2 of $t\bar{t}b\bar{b}$ cross section involves a jet harder than b-jet system
- it is natural to treat it as H-contribution in NLOPS framework

Comparison of S/H separation in various tools

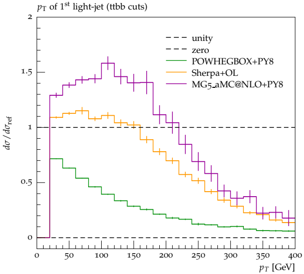
N_b



m_{bb}



p_{T,j_1}



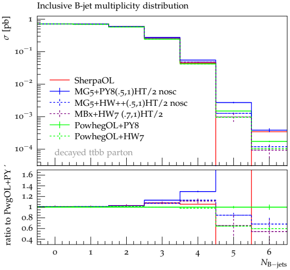
- Powhe: S-contribution $\sim 50\%$, i.e. comparable to $k_T(b\bar{b}) < p_T(\text{jet})$ (as a result of h_{bzd})
- MC@NLO tools: in Sherpa and especially in MG5+PY8, S-contribution overestimates full XS and must be compensated by negative H-contribution

Comparison of 6 MC with top decays (WW4b cuts)

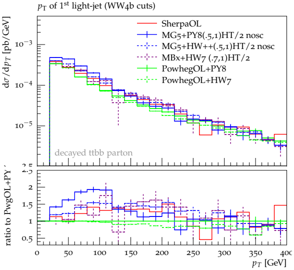
Inputs (here and in the following)

- same inputs as in HXSWG YR4 (but default shower tunes)
- limited statistics

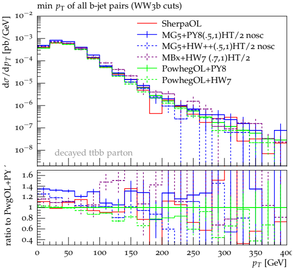
N_b



p_{T,j_1}



$p_{T,bb,\mathrm{min}}$



Features observed with stable tops confirmed

- now 20% spread of $WW + 4b$ XS and factor-2 in jet spectrum

(present studies focussed back on stable $t\bar{t}b\bar{b}$)

Hadronisation effects in $t\bar{t}b\bar{b}$ MC comparisons

Motivation of theory studies w.o. top decays and hadornisation

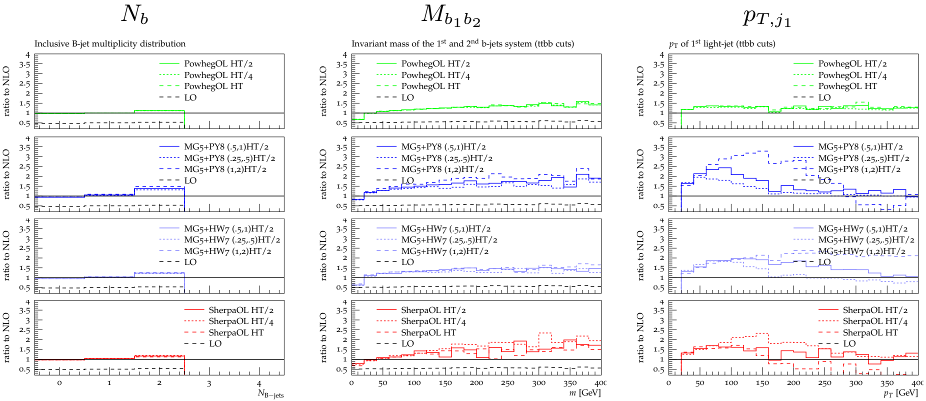
- top decays are trivial (well understood EW interactions) but render the analysis of b-quark production in $WWb\bar{b}b\bar{b}$ final states quite cumbersome
- switching off top decays is very useful in order to investigate the QCD dynamics of b-production in $pp \to t\bar{t}b\bar{b}$ (which dominates TH uncertainties!)
- since top quarks carry SU(3) charge, also hadronisation needs to be switched off

Possible bias of MC comparisions?

- switching off hadronisation could bias comparisons of different showers (Pythia, Sherpa, Herwig) due to dependencies on unphysical dependences (e.g. IR cutoff)
- irrelevant for Powheg+PY8 vs MG5+PY8 comparison (same shower)
- for Sherpa vs MG5+PY8 we have assessed this effect comparing LOPS simulations of $H+b$-jet production (as proxy of $t\bar{t}b\bar{b}$ production) finding non-negligible but rather small hadronisation effects wrt the observed differences in $t\bar{t}b\bar{b}$ production

see `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LOpphHadronisation`

NLOPS/NLO and μ_Q,hdamp dependence



- Powheg very stable
- similar trend but different μ_Q dependence in MG5+PY8, MG5+HW and Sherpa (new recoil scheme)