Theory perspective on understanding ttH/tH (signal and) background

Stefano Pozzorini

based on

T. Jezo, J. Lindert and S.P. [arXiv:1802.00426]

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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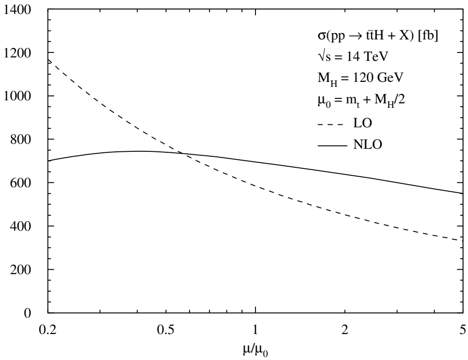
Foreword I

$\sigma_{t\bar{t}H}$ at NLO QCD

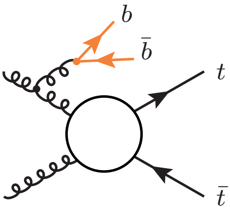
[Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas 2001; Reina, Dawson 2001]



⇒ 10% level precision

⇒ landmark for interpretation of $t\bar{t}H$ discovery

Foreword II



Dominant TH systematics in $t\bar{t}H/tH$ from $t\bar{t}+b$-jet background to $t\bar{t}H(b\bar{b})$

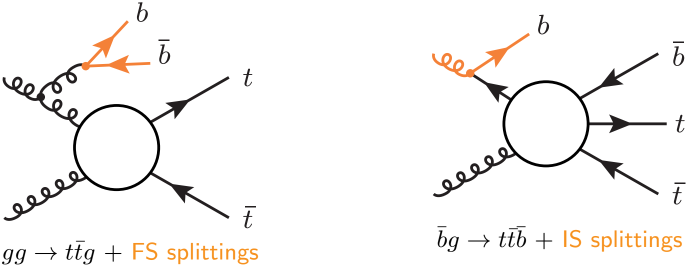
- $t\bar{t}+b$-jet data help, but "extrapolation" to signal region calls for precise theory prediction for $t\bar{t}+b$-jet shapes
- significant sensitivity improvements may be achieved by
  - exploiting increasing variety and precision of $t\bar{t}b\bar{b}$ MC tools
  - improved understanding of $t\bar{t}b\bar{b}$ multi-scale dynamics
  - much closer collaboration between theory and experiments

Outline

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

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



Precision vs accuracy

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

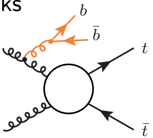
Calls for improved description based on $t\bar{t}b\bar{b}$ MEs

$\Rightarrow$ testable prediction with higher precision and more realistic uncertainties

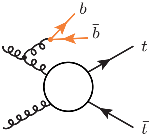
$\Rightarrow$ possible tensions with data more instructive than tuning a non predictive MC!

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

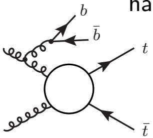
softer b-quarks $\Longleftarrow$



$t\bar{t}$ + PS



$t\bar{t}g$ + PS

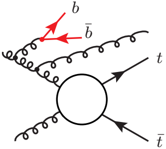


$t\bar{t}b\bar{b}$

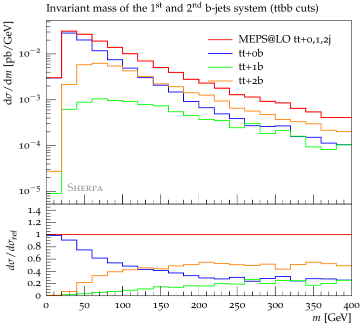
$\Longrightarrow$ harder b-quarks

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

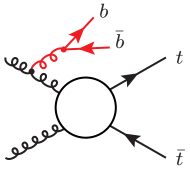
- k_T-resolution cut separates MEs (with $m_b = 0$) from shower (collinear approx.)
- $g \to b\bar{b}$ splittings dominated by parton shower up to $m_{b\bar{b}} \gtrsim$ 100 GeV due to competition with harder light jets

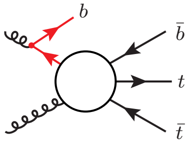


m_{bb} with ttbb cuts

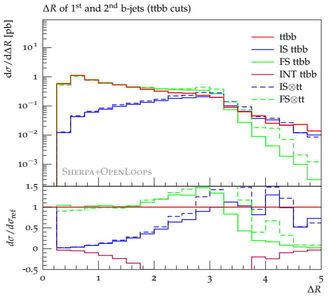


Option 3: NLOPS $t\bar{t}b\bar{b}$ in 4F scheme





ΔR_{bb} with ttbb cuts



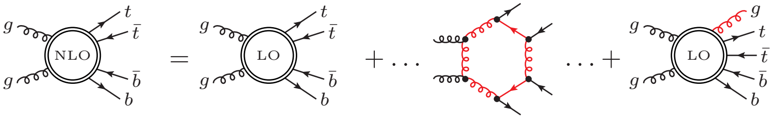
4F $pp \to t\bar{t}b\bar{b}$ MEs with $m_b > 0$ at NLOPS

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

$\Rightarrow$ 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 (in ttbb and ttb phase space)
- negligible $g \to b\bar{b}$ framentation logs beyond NLO at $p_T \lesssim$ 50–100 GeV
  [Mangano, Nason 1992]



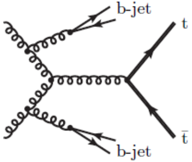
Nontrivial features of $pp \to t\bar{t}b\bar{b}$ at NLO

- 34 LO diagrams and > 1000 NLO diagrams
- 6 external coloured partons
- 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]
- multiple scales from 5 to 500 GeV (gap between $b\bar{b}$ and $t\bar{t}$ systems)

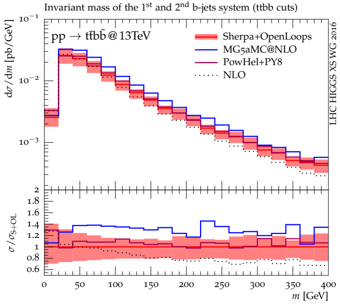
Nontrivial NLOPS issues

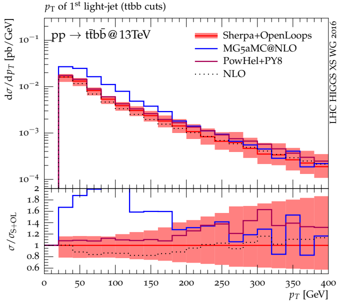
- in Higgs region up to 30% matching/shower effects from double $g \to b\bar{b}$ splittings [Cascioli et al '13]

⇒ crucial to understand $g \to b\bar{b}$ splittings and matching+shower uncertainties



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





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

- 40% NLOPS/NLO enhancement of $t\bar{t} + 2\mathrm{b}$ XS in MG5
- related to sizeable enhancement of NLO radiation at $p_T \sim 100\,\mathrm{GeV}$
- 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?

Outline

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

PowhegBox+OpenLoops [Jezo, Lindert, Moretti, S.P 1802.00426]

4F $t\bar{t}b\bar{b}$ NLOPS generator

- covers full b-quark phase space (see also [Bevilacqua, Garzelli, Kardos, 1709.06915])
- spin-corr. top decays and separation of soft/hard NLOPS radiation for ISR *and* FSR

Very large fixed-order NLO K-factor

- using $\alpha_S^{\rm LO}$ for $\sigma_{\rm LO}$ (typical in $t\bar{t}b\bar{b}$ literature) $\Rightarrow$ $\sigma_{\rm NLO}/\sigma_{\rm LO} \sim 1.2$
- using $\alpha_S^{\rm NLO}$ throughout $\Rightarrow$ $\sigma_{\rm NLO}/\sigma_{\rm LO} \sim 1.9$ applied to NLOPS soft radiation

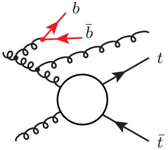
$\Rightarrow$ requires: - careful soft/hard separation of NLOPS radiation

- understanding of origin of large correction $\leftrightarrow$ scale choice

Restriction of soft NLOPS radiation in Powheg ("bornzerodamp")

$$k_T \lesssim h_{\rm damp} = H_T/2 \qquad \text{and} \qquad \frac{R_{\rm soft}(\Phi_R)}{B(\Phi_B)\otimes K_{\rm soft/coll}(\Phi_{\rm rad})} < h_{\rm bzd} = 2$$

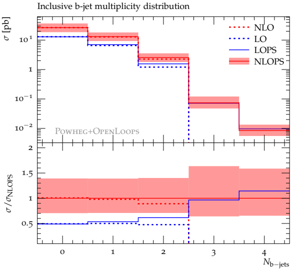
$\Rightarrow$ avoids large K-factor (resummation) in wide regions where $p_{T,b} < k_T < h_{\rm damp}$ and soft/coll factorisation not fulfilled



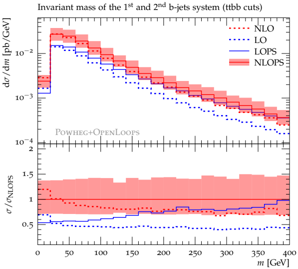
$\Rightarrow$ high stability wrt $h_{\rm damp}$ variations for multiscale process

NLOPS vs NLO Powheg $t\bar{t}b\bar{b}$ predictions [1802.00426]

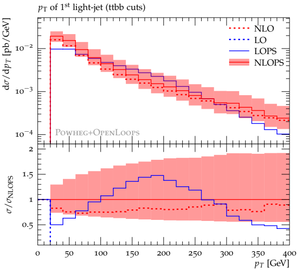
N_b



$M_{b_1 b_2}$



p_{T,j_1}



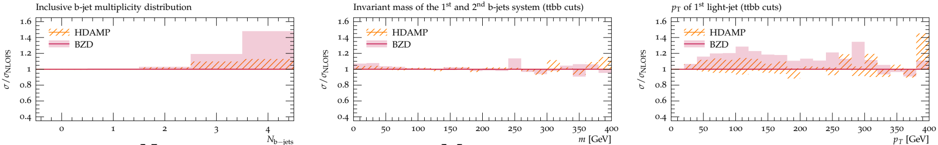
Moderate NLOPS/NLO corrections

- consistent with NLO scale-variation bands
- 10% for σ_{tt+2b} and 20–30% at $m_{bb} \sim 100\,\mathrm{GeV}$ (confirms double splittings)

Shape of light-jet p_T

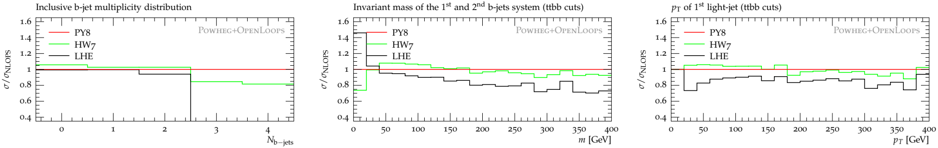
- NLOPS quite similar to fixed-order NLO
- LOPS/NLOPS indicates that PY8 can strongly overestimate radiation at $p_T \sim 200$ GeV (see YR4) but Powheg+PY8 spectrum is NLO-like

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



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

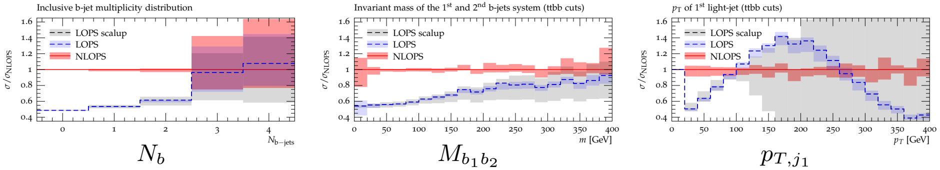
Powheg+PY8 vs Herwig7



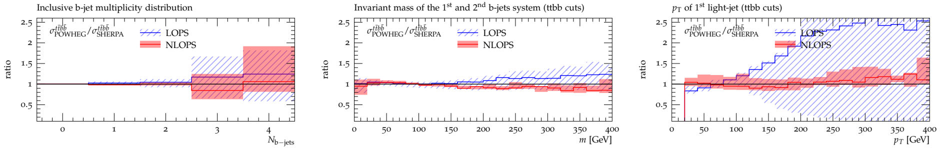
- MC uncertainties << QCD scale dependence: **percent level** for inclusive $t\bar{t} + b$-jet observables and 10–20% level in jet-p_T spectrum
- High stability thanks to $h_{\rm bzd}$ restriction and **independence of $1^{\rm st}$ Powheg emission wrt parton shower**

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



$t\bar{t}b\bar{b}$ 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

5 MC tools, 2 NLOPS methods, 3 showers, 10 contributing authors

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	

Plan and philosophy for theoretically consistent tool comparison

- coherent definition of *intrinsic* MC uncertainties across different tools: separarate, synchronise and vary one-by-one perturbative/matching/shower dependencies
- model leading MC uncertainties based on understanding of underlying physics
- exploit MC comparison (and data) for checks and refinements

$\Rightarrow$ Theory framework for $t\bar{t}+b$-jets systematics for $t\bar{t}H$ and $t\bar{t}b\bar{b}$ analyses at LHC

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}

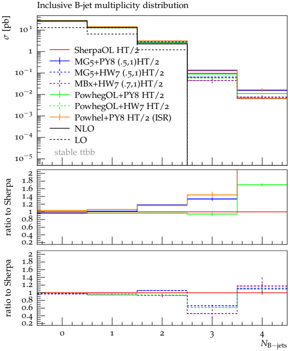
Powheg:	$R_{\text{soft}}(\Phi_R) = R(\Phi_R)\, g_{\text{soft}}(\Phi_1, h_{\text{damp}})$	matrix element
MC@NLO:	$R_{\text{soft}}(\Phi_R) = B(\Phi_B) \otimes K_{\text{shower}}(\Phi_1)\, g_{\text{soft}}(\Phi_1, \mu_Q)$	parton shower

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

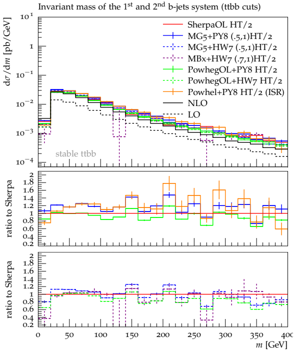
$\Rightarrow$ choose $h_{\text{damp}} = \mu_Q$ and g_{soft} as similar as possible for consistent comparison

MC comparison with $t\bar{t} + 2\mathrm{b}$ cuts

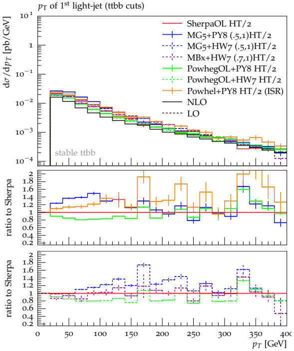
N_b



$M_{b_1 b_2}$



p_{T,j_1}



NLO+PY8 tools vs Sherpa (1st ratio)

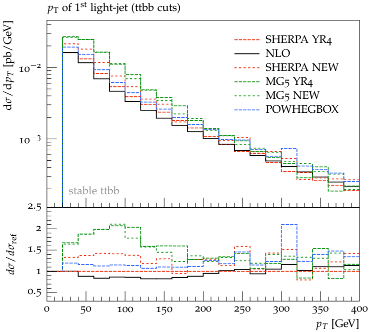
- Powheg+OpenLoops $\simeq$ Sherpa while MG5+PY8 $\simeq$ Powhel+PY8* 20–50% higher

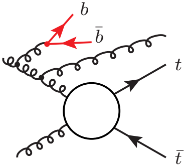
NLO+Herwig tools vs Sherpa (2nd ratio)

- all predictions closer to each other

does not implement h_{damp} restriction of FSR

Distortion of ligh-jet radiation spectrum (normalised to Sherpa YR4)





Current interpretation

$$\frac{\bar{B}_{\rm soft}}{B} \sim \frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}} \sim 2$$

$\Rightarrow$ 100% distortion of jet-p_T spectrum

$$\frac{d\sigma}{d\Phi_B d\Phi_1} = R + \underbrace{\left[\frac{\bar{B}_{\rm soft}}{B}\Delta - 1\right]}_{\gtrsim 100\% \text{ instead of } \mathcal{O}(\alpha_S)} R_{\rm soft}$$

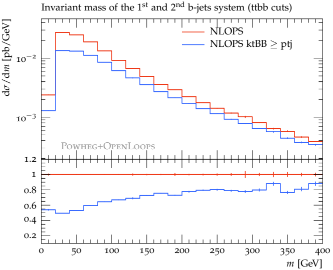
$\Rightarrow$ effect of hard-jet recoil on p_T of soft b-jets induces N_b-bin migrations

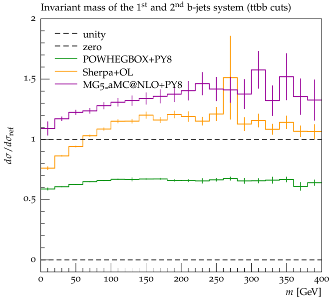
$\Rightarrow$ enhancement of $t\bar{t}$+2b cross section

Depends on relative importance of soft/hard contributions

Soft/hard separation

m_{bb}





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

Conclusions and Outlook

Recent progress towards understanding/reduction of $t\bar{t}+b$-jet uncertainties

- NLOPS $t\bar{t}b\bar{b}$ generators with 8 combinations of matching methods $\otimes$ showers
- systematic framework for intrinsic MC uncertainties and MC comparisons
- increasing understanding of $t\bar{t}b\bar{b}$ multi-scale dynamics

Next steps

- address remaining aspects like perturbative shape uncertainties
- theory recommendations for $t\bar{t}+b$-jet predictions and uncertainties
- . . . ATLAS/CMS feedback and implementation

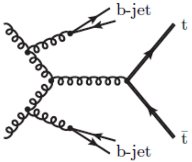
Backup slides

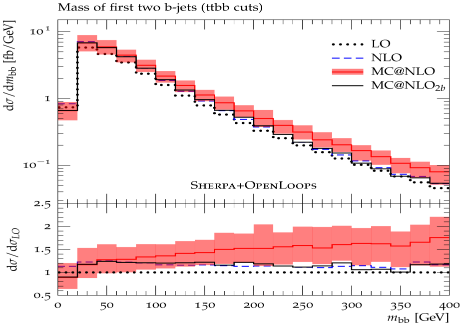
NLOPS $t\bar{t}b\bar{b}$ 4F with Sherpa+OpenLoops [Cascioli et al '13]

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 $p_T = Q$

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

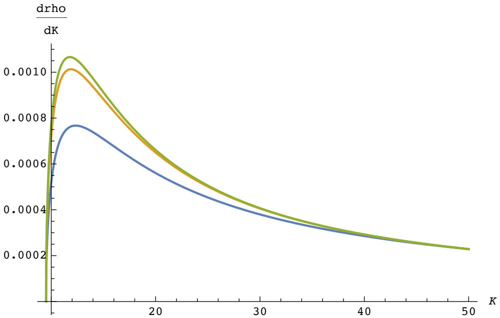
Perturbative expansion in $\alpha_S = \alpha_S(Q^2) = \left[b \ln(Q^2/\Lambda^2)\right]^{-1}$

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

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

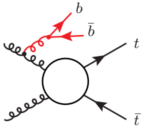
Total $g \to b\bar{b}$ probability

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]

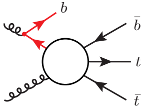
$t\bar{t}b\bar{b}$ topologies with FS $g \to b\bar{b}$ splittings

- 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

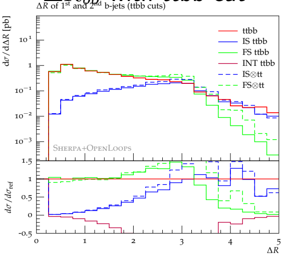


$t\bar{t}b\bar{b}$ topologies with IS $g \to b\bar{b}$ splittings

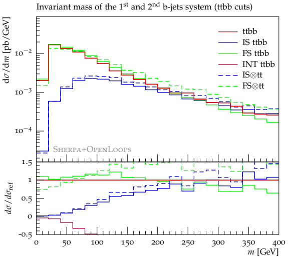
- mostly clearly subdominant (no need for 5F scheme resummation)



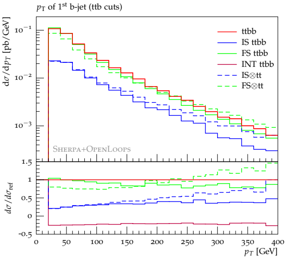
ΔR_{bb} with ttbb cut



m_{bb} with ttbb cuts



p_{T,b_1} with ttb cuts

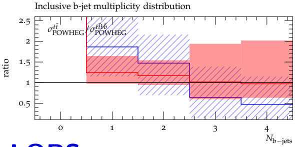


supports choice of 4F scheme with $m_b > 0$ and no b-quark PDF

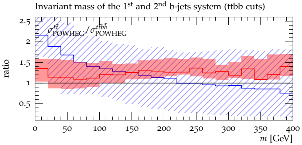
Powheg $t\bar{t}b\bar{b}$ vs Powheg $t\bar{t}$ inclusive [1802.00426]

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

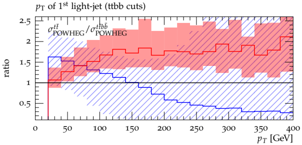
N_b



$M_{b_1 b_2}$



p_{T,j_1}



LOPS

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

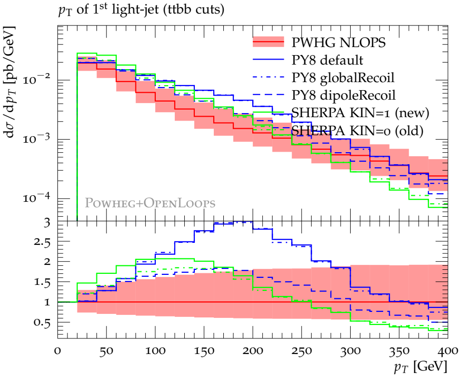
NLOPS

- 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

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

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

Shower and PDFs for showering

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

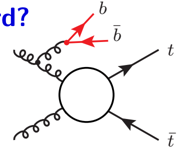
NLOPS subtleties for multi-scale problems [1802.00426]

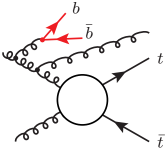
Matching based on factorisation of S-radiation wrt hard $t\bar{t}b\bar{b}$ process

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

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



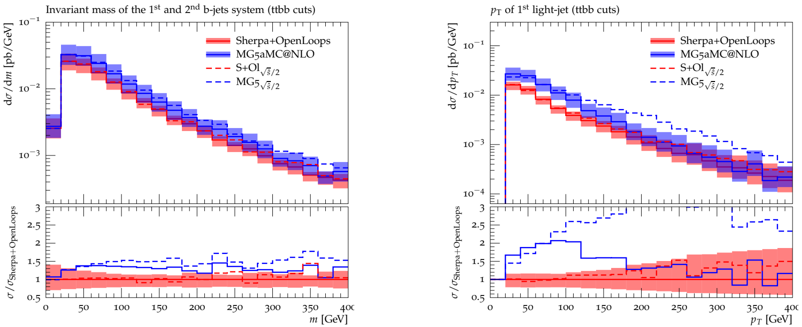


Powheg "safety" system: resummation only if $R_{\text{soft}} < h_{\text{bzd}} \times B \otimes K_{\text{soft/coll}}$

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

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

Dependence on resummation scale μ_Q (shortly after YR4)



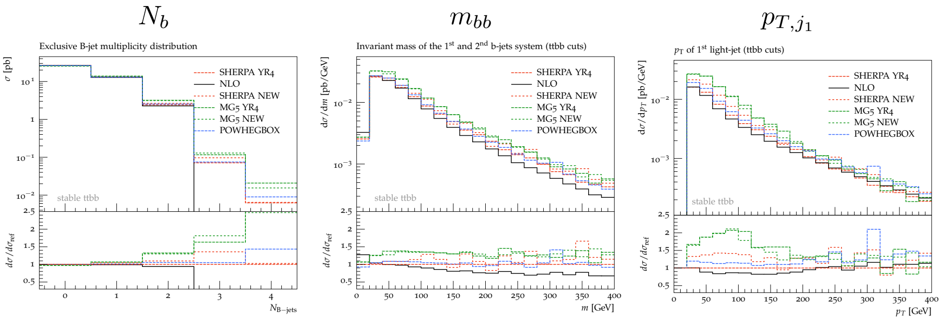
Nominal MG5_aMC and Sherpa+OpenLoops predictions in YR4

- 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]



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

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

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

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

and integrated out in

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

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

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

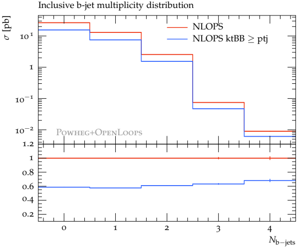
$\Rightarrow$ strongly enhanced positive correction beyond "max resummation": unphysical?

Natural separation approach

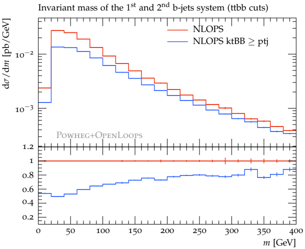
Compare hardness of $g \to b\bar{b}$ splitting to p_T of NLO radiation

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

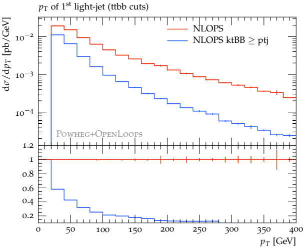
N_b



m_{bb}



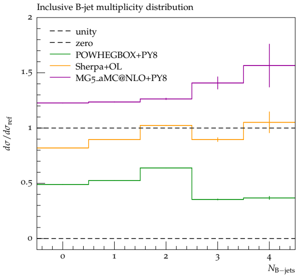
p_{T,j_1}



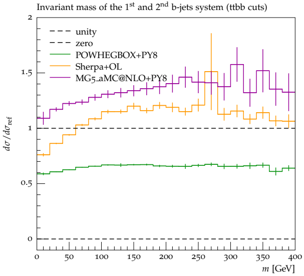
- roughly 1/2 of $t\bar{t}b\bar{b}$ cross section involves a jet harder than b-jet system
- it is natural to treat it as H-contribution in NLOPS framework

Comparison of S/H separation in various tools

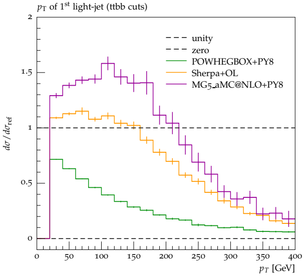
N_b



m_{bb}



p_{T,j_1}



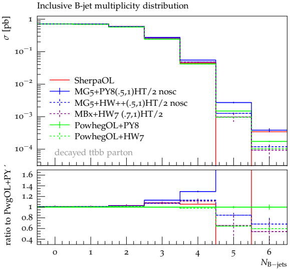
- Powhe: S-contribution $\sim 50\%$, i.e. comparable to $k_T(b\bar{b}) < p_T(\mathrm{jet})$ (as a result of h_{bzd})
- MC@NLO tools: in Sherpa and especially in MG5+PY8, S-contribution overestimates full XS and must be compensated by negative H-contribution

Comparison of 6 MC with top decays (WW4b cuts)

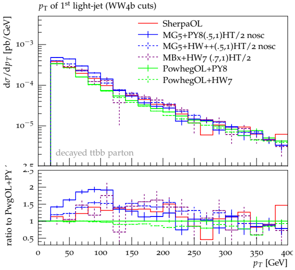
Inputs (here and in the following)

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

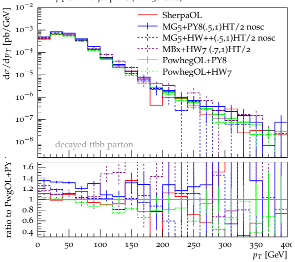
N_b



p_{T,j_1}



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



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

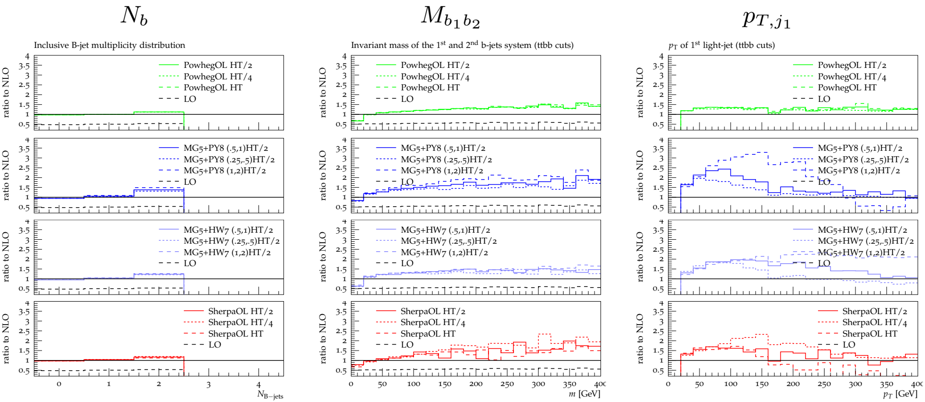
- top decays are trivial (well understood EW interactions) but render the analysis of b-quark production in $WWb\bar{b}b\bar{b}$ final states quite cumbersome
- switching off top decays is very useful in order to investigate the QCD dynamics of b-production in $pp \to t\bar{t}b\bar{b}$ (which dominates 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)