$t\bar{t}$+HF theory predictions

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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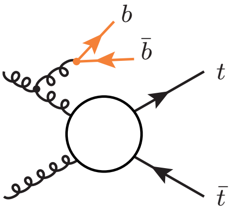
Foreword



$t\bar{t}H(b\bar{b})$ searches dominated by theory systematics of $t\bar{t}+b$-jet background

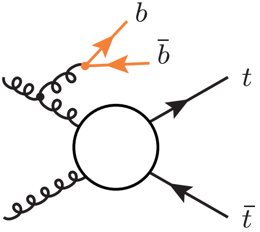
- $t\bar{t}+b$-jet data help, but precise "extrapolation" to signal region calls for $t\bar{t}+b$-jet shape uncertainties at 10% level ...
- variety of NLO MC tools available for $pp \to t\bar{t}b\bar{b}$ ...
- ... but $pp \to t\bar{t}b\bar{b}$ remains a nontrivial multi-particle multi-scale QCD process
- better understanding of its QCD dynamics and NLOPS theory systematics crucial for assessment of TH uncertainties

Outline

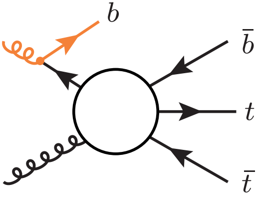
1. 4F $t\bar{t}b\bar{b}$ vs other simulation approaches
2. New Powheg 4F $t\bar{t}b\bar{b}$ generators
3. Ongoing NLOPS $t\bar{t}b\bar{b}$ studies within HXSWG

Option 1: 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

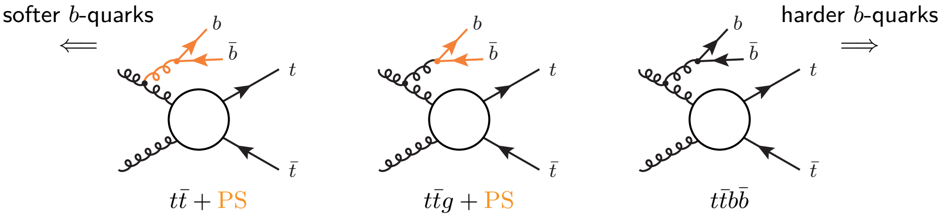
Calls for improved description based on $t\bar{t}b\bar{b}$ MEs

⇒ testable prediction with higher precision and more realistic uncertainties

⇒ 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

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



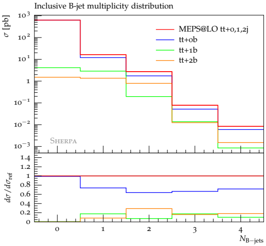
Merging cut Q_{cut}

- separates ME regions ($k_T > Q_{\text{cut}}$) from shower regions ($k_T < Q_{\text{cut}}$)
- low Q_{cut} maximises precision but can lead to prohibitive CPU cost at NLO
- in 5F scheme finite Q_{cut} mandatory to avoid $g \to b\bar{b}$ singularity of MEs with $m_b = 0$

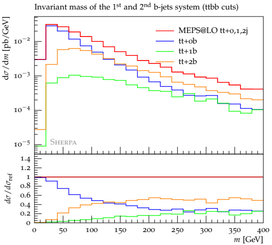
$t\bar{t}b\bar{b}$ mostly from shower in $t\bar{t}$+multi-jet merging [1802.00426]

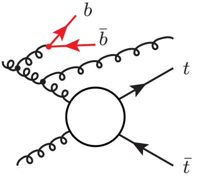
$t\bar{t} + 0, 1, 2$ jet LO merging with $Q_{\text{cut}} = 20\,\text{GeV}$

$N_{b\,\text{jets}}$



m_{bb} with ttbb cuts



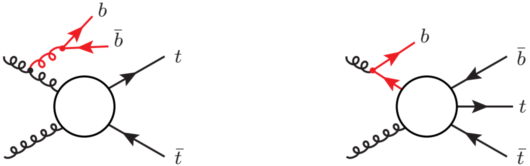


Observables with ≥ 1 additional b-jets

- dominated by MEs with 2 light jets and no b-jets (up to $Q \sim 100\,\text{GeV}$)!
- due to the fact that $g \to b\bar{b}$ typically softer wrt 1st and 2nd splitting

$\Rightarrow$ **direct description in terms of $t\bar{t}b\bar{b}$ MEs seems preferable**

Option 3: (N)LOPS $t\bar{t}b\bar{b}$ in 4F scheme



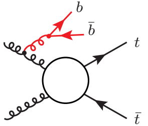
4F $pp \to t\bar{t}b\bar{b}$ MEs with $m_b > 0$ at NLO+PS

- describe full b-quark phase space

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

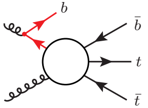
- 80% LO uncertainty reduced to 20–30% at NLO [Bredenstein et al. '09–'10; Bevilacqua et al. '10]
- include b-jet production from IS and FS $g \to b\bar{b}$ collinear splittings

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

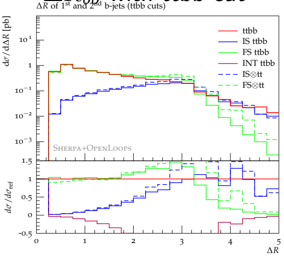
- dominant in full ttbb and ttb phase space
- notion of $g \to b\bar{b}$ splittings and IS/FS separation seems ill defined at large ΔR_{bb}, m_{bb}, $p_{T,b}$ due to sizable interferences



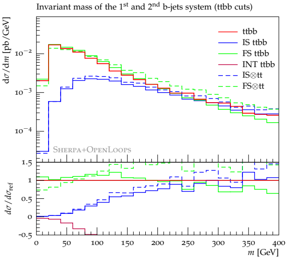
$t\bar{t}b\bar{b}$ topologies with IS $g \to b\bar{b}$ splittings

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

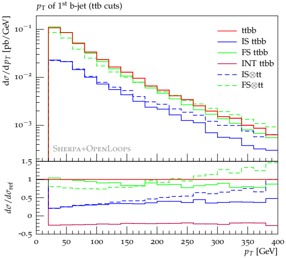
ΔR_{bb} with ttbb cut



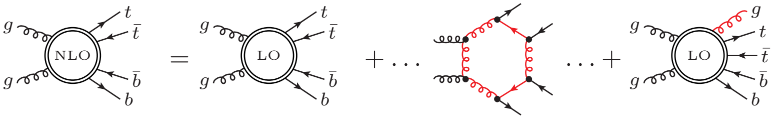
m_{bb} with ttbb cuts



p_{T,b_1} with ttb cuts



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

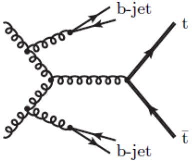


Nontrivial features of $pp \to t\bar{t}b\bar{b}$ at NLO

- 34 LO diagrams and > 1000 NLO diagrams
- 6 external coloured partons
- large uncertainty from $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R)$
- multiple scales from 5 to 500 GeV (gap between $b\bar{b}$ and $t\bar{t}$ systems)

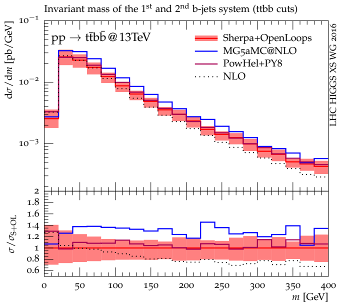
Nontrivial NLOPS issues

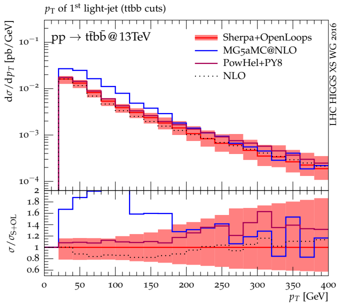
- matching/shower effects up to 30% in Higgs region
- due to double $g \to b\bar{b}$ splittings [Cascioli et al '13]



$\Rightarrow$ 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 $t\bar{t}+2b$ 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 (still open): 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?

Recent news

- now MG5 supports H_T-based resummation scale $\mu_Q = f(\xi)H_T/2$
- two new Powheg 4F $t\bar{t}b\bar{b}$ generators [arXiv:1709.06915, arXiv:1802.00426]
- new MatchBox+Herwig 4F $t\bar{t}b\bar{b}$ generator

$\Rightarrow$ ongoing campaign of $t\bar{t}b\bar{b}$ MC studies within HXSWG

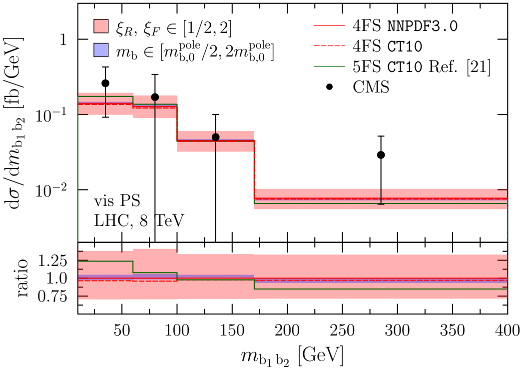
Outline

Original 5F $t\bar{t}b\bar{b}$ Powhel upgraded to 4F scheme with $m_b > 0$

⇒ now applicable to entire b-jet phase space!

⇒ consistent comparison against other 4F $t\bar{t}b\bar{b}$ generators possible

Comparison to 8 TeV CMS data (20/fb) (agreement but statistics still low)



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

Differences wrt Powhel

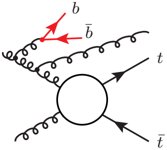
- PowhegBox–RES framework and OpenLoops MEs ($\Rightarrow$ fast)
- spin-correlated top decays
- separation of soft/hard radiation extended to FS radiation

Restriction of soft (resummation) region

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

$\Rightarrow$ avoids resummation in regions $p_{T,b} < k_T < h_{\mathrm{damp}}$ where soft/coll factorisation not fulfilled

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

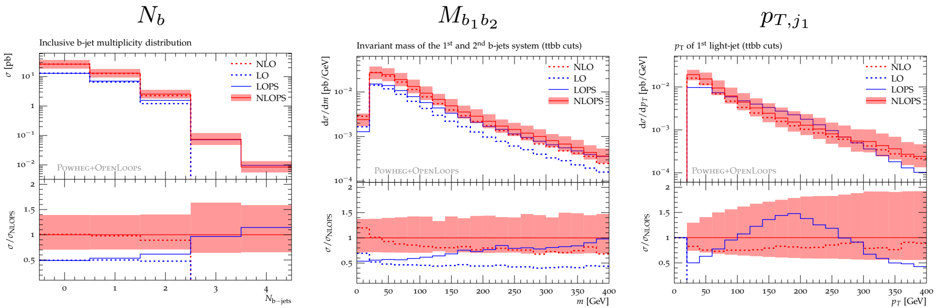


Very large NLO K-factor

- Typically in $t\bar{t}b\bar{b}$ literature: $\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} \sim 1.2$ based on LO inputs for σ_{LO}
- Using NLO inputs throughout (like in NLOPS local K-factor): $\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} \sim 1.9$

$\Rightarrow$ origin of large correction and perturbative convergence to be understood!

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



Moderate NLOPS/NLO corrections within scale-variation bands

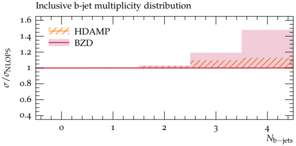
- 10% for σ_{tt+2b}
- 20–30% at $m_{bb} \sim 100\,\mathrm{GeV}$ (double splittings)

Shape of light-jet p_T

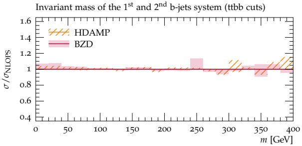
- NLOPS quite similar to fixed-order NLO
- LOPS/NLOPS suggests that PY8 overestimates radiation with $p_T \sim 200\,\mathrm{GeV}$
  $\Rightarrow$ related to effects in MG5+PY8?

Intrinsic NLOPS uncertainties of Powheg $t\bar{t}b\bar{b}$ [1802.00426] I

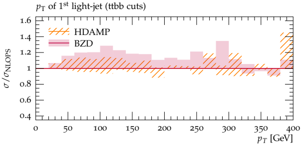
N_b



$M_{b_1 b_2}$



p_{T,j_1}

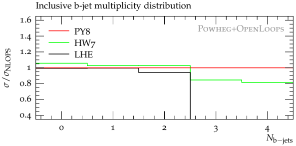


Dependence on matching scales ($h_{\rm damp} = H_T/4, H_T/2, H_T, 1.5 m_t$ and $h_{\rm bzd} = 2, 5, 10$)

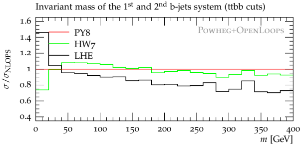
- inclusive $t\bar{t} + b$-jet observables remarkably stable at percent level
- jet-p_T spectrum stable at 10–20% level

High stability guaranteed by $h_{\rm bzd}$ restriction of Powheg resummation

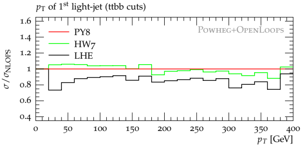
N_b



$M_{b_1 b_2}$



p_{T,j_1}



LHEs vs NLOPS

- Significant NLOPS effects in m_{bb} (double splittings)

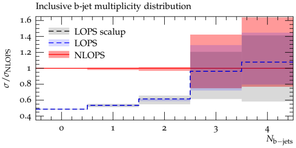
Powheg+Pythia8 vs Powheg+Herwig

- dependence on choice of parton shower $<<$ QCD scale dependence

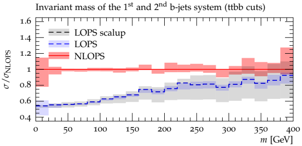
High stability thanks to independence of 1^{st} Powheg emission wrt parton shower

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

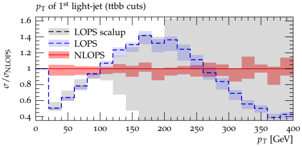
N_b



$M_{b_1 b_2}$



p_{T,j_1}



LOPS variations dominated by factor-2 variations of scalup$=H_T/2$

- strongly reduced at NLO, especially for jet-p_T

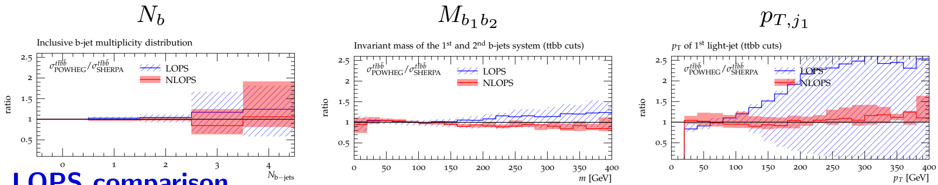
NLOPS variations dominated by $g \to b\bar{b}$ modeling and α_S variations in PY8

- remarkably small NLOPS uncertainties
- again because 1^{st} Powheg radiation independent of shower
- double-splitting effects stable wrt variations of $g \to b\bar{b}$ in PY8

Powheg $t\bar{t}b\bar{b}$ vs other (N)LOPS tools I

$t\bar{t}b\bar{b}$ Powheg+PY8 vs Sherpa

- Powheg with all matching+shower (no scale) uncertainties vs nominal Sherpa



LOPS comparison

- radiation of Sherpa shower less hard than PY8

⇒ likely to have beneficial effects on MC@NLO matching in Sherpa

(while Powheg matching does not suffer from PY8 excess)

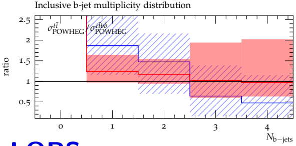
NLOPS comparison

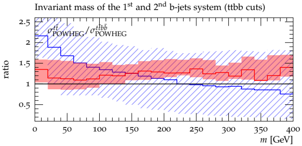
- NLOPS uncertainties and Powheg/Sherpa differences clearly reduced at NLO
  ⇒ different showers and matching methods agree at better than 10% level!
- using Sherpa 2.2 recoil scheme yields more significant (but still moderate) differences (see later)

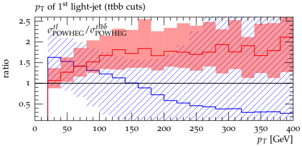
Powheg+PY8: $t\bar{t}b\bar{b}$ vs inclusive $t\bar{t}$

- all 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-$p_{\rm T}$ tail)

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

Outline

Idea and goals

Main goal: $t\bar{t}b\bar{b}$ theory uncertainty estimates for $t\bar{t}H(b\bar{b})$

- comparing MC against data not sufficient since MC needed for extrapolations
- comparing different NLOPS MC tools is (only) the starting point ...
- ... we need intrinsic uncertainty of individual MC $\Rightarrow$ should explain MC differences

Roadmap

- optimal choice of settings for coherent (apple-to-apple) comparison
- variations to isolate/rank uncertainties of fixed-order, matching and shower origin
- identify+understand leading sources of MC differences/uncertainties
- TH uncertainties recommendations (for $t\bar{t}H$ searches and $t\bar{t}b\bar{b}$ measurements)

$\Rightarrow$ Uniform framework for $t\bar{t}+b$-jets TH systematics in ATLAS+CMS

Status https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalWwbbbb

- preliminary results (also limited by MC statistics)
- no conclusion but good progress and interesting open questions/hypotheses

Rivet analysis and tools

New $t\bar{t}b\bar{b}$ Rivet analyses for HXSWG comparisons (J. Lindert, T. Jezo)

- with stable tops (extended wrt YR4): 60 observables (ttb and ttbb cuts)
- with dileptonic top decays: 84 observables (WW4b and WW3b cuts)
- public results ⇒ benchmarks for MC simulation in ATLAS/CMS and theory

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

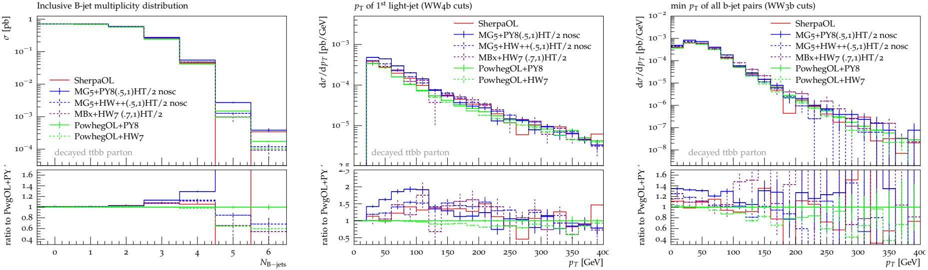
Tool	MC@NLO	Powheg	Pythia 8.2	Herwig 7.1.2	Sherpa2.2.4	MC contacts
SHERPA2.2+OPENLOOPS	x				x	F. Siegert, J. Krause
MG5_AMC@NLO	x		x	x		M. Zaro
MATCHBOX+OPENLOOPS	x			x		C. Reuschle, R. Posdkubka
POWHEG+HELAC		x	x	x		M.V. Garzelli, A. Kardos
POWHEGBOX+OPENLOOPS		x	x	x		T. Jezo, J. Lindert
	3	2	3	4	1	

Comparison 6 MC with top decays (WW4b cuts)

Inputs (here and in the following)

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

N_b $\qquad$ p_{T,j_1} $\qquad$ $p_{T,bb,\min}$



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

How to interpret MC comparison

Different types of dependencies

- parton shower choice and tune
- choice of matching method and related parameters
- perturbative apsects (QCD scales, PDFs)

Idea

- disentangle perturbative/matching/shower dependence
- in particular: isolate irreducible differences due to matching method

Ongoing discussion on matching settings tricky but instructive...

MC@NLO vs Powheg matching (how to compare?)

Splitting of radiation: S-events (soft/singular) and H-events (hard/remnant)

$$\mathrm{d}\sigma_S = \mathrm{d}\Phi_B \bar{B}(\Phi_B)\left[\Delta(t_{\mathrm{IR}}) + \Delta(k_T)\frac{R_{\mathrm{soft}}(\Phi_R)}{B(\Phi_B)}\,\Phi_{\mathrm{rad}}\right] \qquad \mathrm{d}\sigma_H = \mathrm{d}\Phi_R\left[R(\Phi_R) - R_{\mathrm{soft}}(\Phi_R)\right]$$

Soft radiation integrated out in $\bar{B}$ $\Rightarrow$ $\bar{B}/B$ = local K-factor

$$\bar{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int \mathrm{d}\Phi_{\mathrm{rad}} R_{\mathrm{soft}}(\Phi_B, \Phi_{\mathrm{rad}})$$

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

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

Soft profile $g_{\mathrm{soft}}(\Phi_{\mathrm{rad}}, \mu_Q)$

- restricts R_{soft} below μ_Q (resummation scale), e.g. $\theta(\mu_Q^2 - k_T^2)$

$\Rightarrow$ **ideal choice for consistent comparison**: $h_{\mathrm{damp}} = \mu_Q$ and same g_{soft} ...?

Choice of shower starting scale (separation of S/H events)

Implementation of scalup **based on recommendation** $\mu_Q = h_{\mathrm{damp}} = H_T/2$

- different choices of S- and H-events (scalup_S, scalup_H)
- distributed with different profiles: see $(\mathrm{scalup}_{\mathrm{mean}}, \mathrm{scalup}_{\mathrm{max}})$ in the table

MC	method	scalup_S	scalup_H	comments
MG5	MC@NLO	$(.55, 1)\mu_Q$	$(1, 1)\mu_Q$	
MatchBox	MC@NLO	$(.7, 1)\mu_Q$	$(.7, 1)\mu_Q$	
Sherpa	MC@NLO	$(1, 1)\mu_Q$	1st k_T or μ_Q	
PowhegOL	Powheg	ME	1st k_T	no scalup dependence
Powhel	Powheg	ME	1st k_T	no scalup dependence

Comments

- MG5 authors "synchronise" $\mathrm{scalup}_{\mathrm{max}} \Rightarrow \mathrm{scalup}_{\mathrm{mean}} \sim H_T/4$ (no consensus so far)
- important: study scalup_S and scalup_H dependence separately

Choice of PDFs+α_S (studies by M.Zaro see next breakout session)

Employed PDFs+α_S values

	label	scheme and PDFs	$\alpha_S(M_Z)$	α_S/α_S^{4F}
Fixed-order NLO	4F NLO	NNPDF30_nlo_af_0118	0.112	1
HW7 showering	5F LO PS	MMHT14 LO (HW tune)	0.1262	1.125
PY8 showering	5F LO PS	NNPDF2.3 QCD+QED LO (Monash)	0.1365	1.219

MC implementation

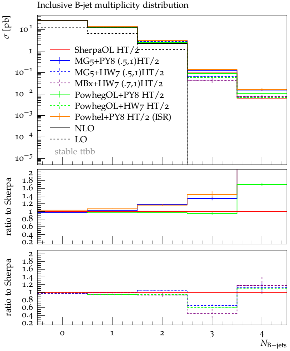
MC	method	$\bar{B}$	1st emission H-event	1st emission S-event	higher emissions
PowhegOL	Powheg	4F NLO	4F NLO	4F NLO	5F LOPS
Powhel	Powheg	4F NLO	4F NLO	4F NLO	5F LOPS
Sherpa	MC@NLO	4F NLO	4F NLO	4F NLO	4F NLO
MG5	MC@NLO	4F NLO	4F NLO	5F LOPS	5F LOPS
MatchBox	MC@NLO	4F NLO	4F NLO	5F LOPS	5F LOPS

Open questions

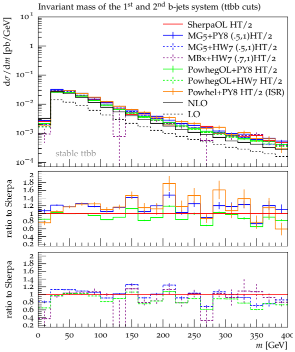
- S-radiation with 5F LO PDF $\Rightarrow$ jet-p_{T} spectrum with too large α_S
- use PS tunes with reasonable α_S?
- consistency issues also from $b \to bg$ ISR in 1st emission?

Comparison with stable tops (ttbb cuts)

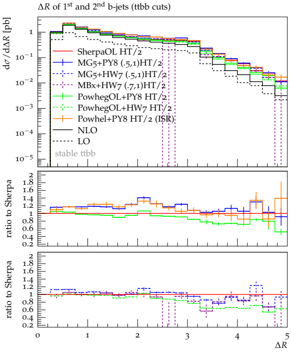
N_b



$M_{b_1 b_2}$

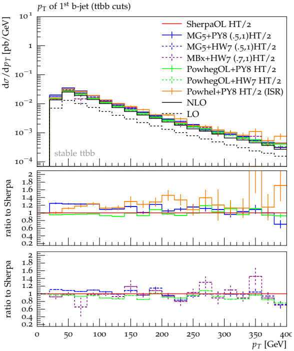


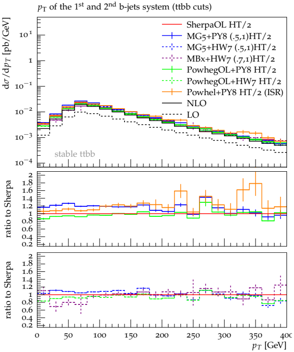
$\Delta R_{b_1 b_2}$

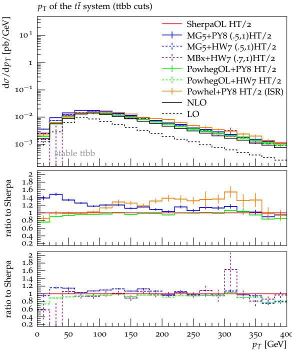


- NLOPS+PY8 and Sherpa predictions (1st ratio):
  PowhegOL $\simeq$ Sherpa while MG5+PY8 $\simeq$ Powhel+PY8 (lack of FS h_{damp}?)
- NLOPS+HW7 and Sherpa predictions closer to each other

p_{T,b_1} $p_{T,b_1 b_2}$ $p_{T,t\bar{t}}$

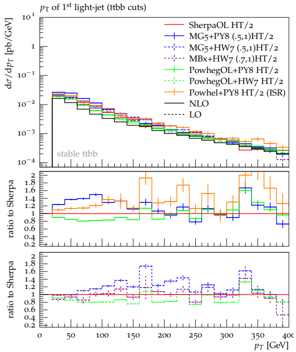






- in general good agreement in shape of inclusive observables
- different shapes of MG5+PY8 and Powhel+PY8 in p_T of $t\bar{t}$

Spectrum of ligh-jet radiation



Familiar picture of MC differences

- Normalisation changed a bit, but YR4-like shape differences persist

Current interpretation (hypothesis)

- large local K-factor applied to soft events distorts jet-p_T spectrum
- no effect on total XS, but related recoil can shift b-jet p_T

$\Rightarrow$ migrations between different N_b bins

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

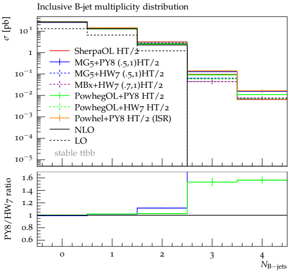
Effect depends on relative importance of S/H contributions

- can be ehnanced in MG5+PY8 due to
  - scalup implementation = soft profile (theory uncertainty)
  - overestimate of soft radiation by PY8 (in part unphysical)

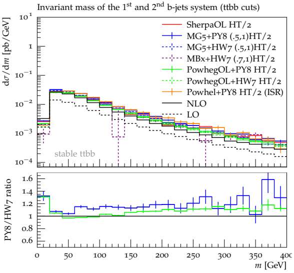
To be discussed!

PY8/HW7 (in MG5 and Powheg+OL)

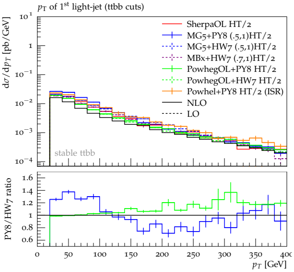
N_b



$M_{b_1 b_2}$



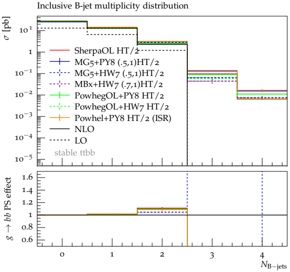
p_{T,j_1}



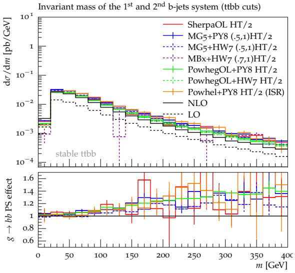
- PowhegOpenLoops more stable
- aMC_MG5+Herwig closer to the other MC tools

Relative effect of double $g \to b\bar{b}$ splittings (for 5 MCs)

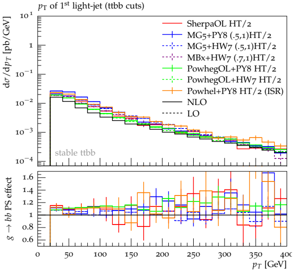
N_b



$M_{b_1 b_2}$

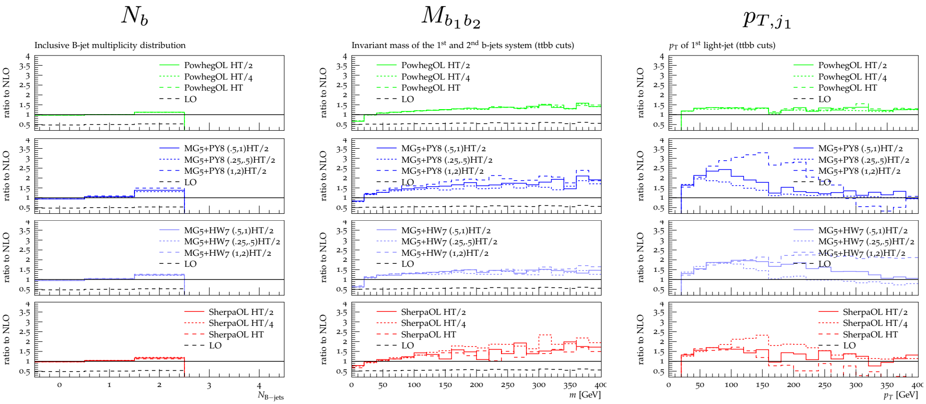


p_{T,j_1}



- does not explain sizable shape differences

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)

Conclusions and Outlook

8 different 4F $t\bar{t}b\bar{b}$ NLOPS tools

- opportunity to disentangle and understand sources of TH uncertainty
- contribution of MC authors crucial: many thanks!

Important goals still ahead of us

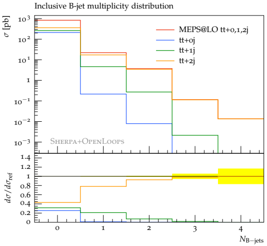
- achieve consensus on interpretation of tool differences/uncertainties
- address perturbative uncertainties, in particular for shapes (see backup slides)

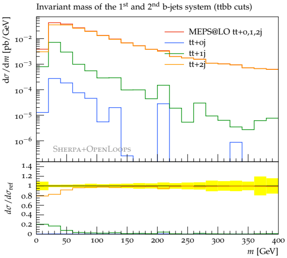
$\Rightarrow$ thorough recommendations for $t\bar{t} + b$-jet theory uncertainty estimates

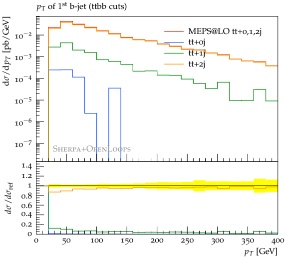
Backup slides

Amount of $t\bar{t}b\bar{b}$ ME information $Q_{\rm cut} = 20\,{\rm GeV}$ (low!)

Generic jet content of $t\bar{t} + 0, 1, 2$ jet LO merging



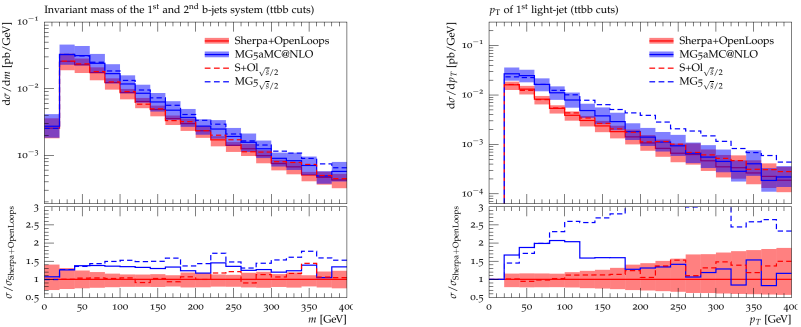




Cross sections and distributions with ≥ 1 additional b-jets

- dominated by $t\bar{t} + 2$ jet MEs . . .

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

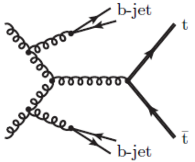
* Ongoing studies with new MG5 version supporting $H_T/2$. See talks by Zaro & Neu.

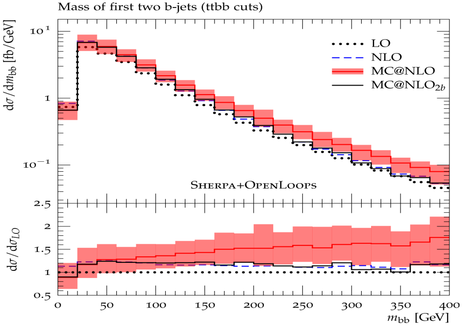
NLOPS $t\bar{t}b\bar{b}$ 4F with SHERPA+OPENLOOPS [Cascioli et al '13]

Convergence of 4F scheme but unexpected MC@NLO enhancement

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

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

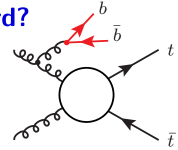
- A14 Pythia tune with $\alpha_S(M_Z) = 0.127$
- NNPDF2.3 LO 5F PDFs

NLOPS subtleties for multi-scale problems [1802.00426]

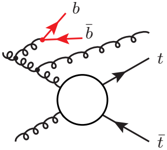
Matching based on factorisation of S-radiation wrt hard $t\bar{t}b\bar{b}$ process

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

What about radiation with $p_{T,b} < k_T < h_{\rm damp}$? 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



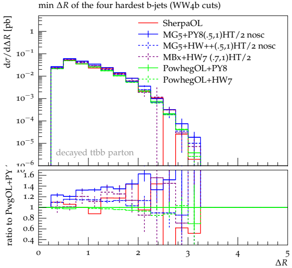
Powheg "safety" system: resummation only if $R_{\rm soft} < h_{\rm bzd} \times B \otimes K_{\rm soft/coll}$

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

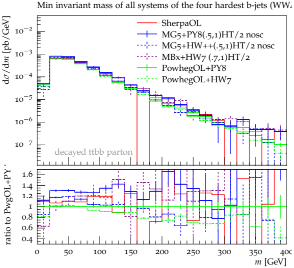
$\Rightarrow$ high stability wrt $h_{\rm damp}$ variations

More observables with top decays (limited statistics)

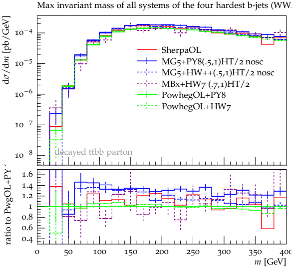
$\Delta R_{bb,\mathrm{min}}$



$M_{bb,\mathrm{min}}$

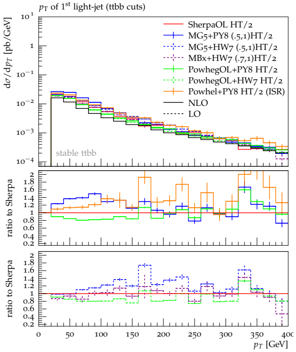


$M_{bb,\mathrm{max}}$

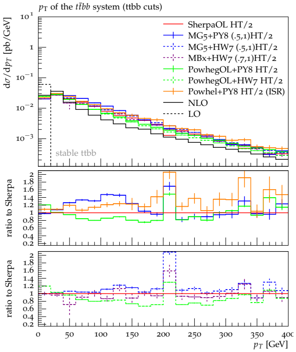


Spectrum of ligh-jet radiation

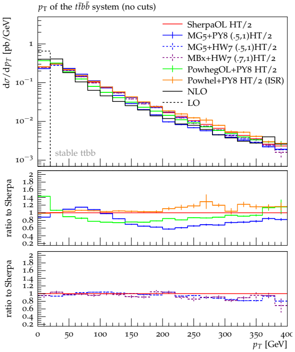
p_{T,j_1}



$p_{T,t\bar{t}b\bar{b}}$ (ttbb cuts)



$p_{T,t\bar{t}b\bar{b}}$ (no cuts)



- familiar picture in spectrum of radiation/recoil spectrum
- normalisation changes but shape different persists if b-jet cuts removed
- hypotheis: distortion of jet-spectrum due to large local K-factor and different S/H separation

⇒ jet recoil transferred to b-jets ⇒ b-jet bin migrations

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

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

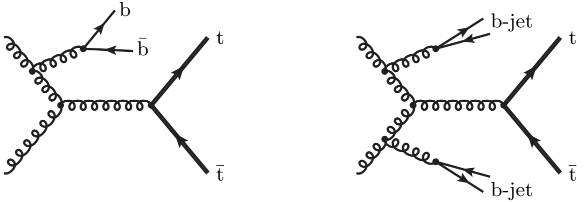
- top decays are trivial (well understood EW interactions) but render the analysis of b-quark production in $WWb\bar{b}b\bar{b}$ final states quite cumbersome
- switching off top decays is very useful in order to investigate the QCD dynamics of b-production in $pp \to t\bar{t}b\bar{b}$ (which dominates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

Why NLO Matching for $t\bar{t}b\bar{b}$ Production in 4F (and not 5F) Scheme



5F scheme ($m_b = 0$): $t\bar{t}b\bar{b}$ MEs cannot describe collinear $g \to b\bar{b}$ splittings

⇒ *inclusive* $t\bar{t}$+b-jets simulation (quite important for exp. analyses!) requires $t\bar{t}$g+PS, i.e. $t\bar{t}+ \leq 2$ jets NLO merging [Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]

see talk by F. Krauss

4F scheme ($m_b > 0$): $t\bar{t}b\bar{b}$ MEs cover full b-quark phase space

⇒ MC@NLO $t\bar{t}b\bar{b}$ sufficient for inclusive $t\bar{t}$+b-jets simulation

- access to **new $t\bar{t} + 2$b-jets production mechanism** wrt 5F scheme: double collinear $g \to b\bar{b}$ splittings (surprisingly important impact on $t\bar{t}H(b\bar{b})$ analysis!)

Sherpa's MC@NLO master formula [Frixione, Webber '02; Höche, Krauss, Schönherr, Siegert '11]

$$\sigma_n^{\mathrm{MC@NLO}} = \int \mathrm{d}\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \mathcal{B}(\Phi_n) \otimes \mathcal{I}\right] \left\{\Delta(\mu_Q^2, t_{\mathrm{IR}}) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{S}(\Phi_1)\, \Delta(\mu_Q^2, t)\right\} + \int \mathrm{d}\Phi_{n+1} \left[\mathcal{R}(\Phi_{n+1}) - \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1)\right]$$

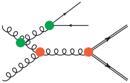
- shower resummation effectively acts starting from $\mathcal{O}(\alpha_s^2)$, and iterated emissions yield fully realistic events
- inclusive observables with n $(n+1)$ particles preserve NLO (LO) accuracy

Factorisation and Resummation scales (available phase space for QCD emission)

$$\mu_{\mathrm{F}} = \mu_Q = \frac{1}{2}(E_{\mathrm{T,t}} + E_{\mathrm{T,\bar{t}}})$$

Scale choice crucial due to $\alpha_S^4(\mu^2)$ dependence (80% LO variation)

- widely separated scales $m_b \leq Q_{ij} \lesssim m_{t\bar{t}b\bar{b}}$ can generate huge logs
- CKKW inspired scale adapts to b-jet p_{T} and guarantees good pert. convergence



$$\mu_{\mathrm{R}}^4 = E_{\mathrm{T,t}} E_{\mathrm{T,\bar{t}}} E_{\mathrm{T,b}} E_{\mathrm{T,\bar{b}}} \quad \Rightarrow \quad \alpha_S^4(\mu_{\mathrm{R}}^2) = \alpha_S(E_{\mathrm{T,t}}^2)\alpha_S(E_{\mathrm{T,\bar{t}}}^2)\alpha_S(E_{\mathrm{T,b}}^2)\alpha_S(E_{\mathrm{T,\bar{b}}}^2)$$

Approach proposed in YR4

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

- can be applied in its full phase space (no generation cuts)

⇒ inclusive description of $t\bar{t}+\geq 1b$-quarks

- includes also contributions corresponding to $gb \to t\bar{t}b$ in the 5F scheme

Inclusive $t\bar{t}+X$ sample

- needs to be restricted to $t\bar{t}+0\,b$-quarks to avoid double counting

⇒ veto events containing b-quarks not arising from showered top decays or MPI or UE

Possible implementations

- $t\bar{t}+X$ and $t\bar{t}b\bar{b}$ samples independent samples
- reweighting of $t\bar{t}+X$ sample through $t\bar{t}b\bar{b}$ in the $t\bar{t}+\geq 1b$-quarks region

Refinement for region of small $p_{T,b}$

Caveat

- $t\bar{t}b\bar{b}$ sample yields (small) contribution to $t\bar{t}+0\,b$-jet categories of EXP analysis
- $t\bar{t}+0\,b$-jet categories (dominated by $t\bar{t}$+gluons/light-quarks) can bias $t\bar{t}b\bar{b}$ fit

$\Rightarrow$ preferable to restrict $t\bar{t}b\bar{b}$ to $t\bar{t}+b$-jet categories

Proposal: smooth matching of $t\bar{t}+X$ and $t\bar{t}b\bar{b}$ samples

- using smearing function of leading b-jet p_T, such as

$$\xi(p_{T,b}) = \begin{cases} 0 & \equiv \text{ pure } t\bar{t}+0b & \text{for} \quad p_{T,b} < p_{T,\min} \\ \frac{1}{2}\left[1-\cos\left(\pi\frac{p_{T,b}-p_{T,\min}}{p_{T,\max}-p_{T,\min}}\right)\right] & & \text{for} \quad p_{T,\min} < p_{T,b} < p_{T,\max} \\ 1 & \equiv \text{ pure } t\bar{t}+\geq 1b & \text{for} \quad p_{T,b} > p_{T,\max} \end{cases}$$

- with transition region in the vicinity of experimental b-jet threshold, e.g. $[p_{T,\min}, p_{T,\max}] = [15, 25]$ GeV
- same matching procedure should be used in ATLAS and CMS for a transparent comparison and combination of EXP results

Scale choices (YR4) and uncertainties (no proposal yet)

Factorisation (μ_Q) and resummation (μ_Q) scales

$$E_{T_i} = \sqrt{m_i^2 + p_{T,i}^2}$$

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

$\mu_Q \equiv$ shower starting scale is a free paramater in MC@NLO (not in Powheg)

CKKW-like (softer) renormalisation scale

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

Scale variations (leading uncertainty) ~20-30%

- factor-2 variations of μ_R and μ_F $\Leftrightarrow$ normalisation
- "kinematic" variations of μ_R, μ_F, μ_Q $\Leftrightarrow$ shape
- variations of μ_Q in MC@NLO and h_{damp} in Powheg $\Leftrightarrow$ NLOPS matching

Other variations

- PDF variations (only few percent)
- shower variations: tune variations, shower recoil scheme, . . .

Correlation of TH uncertainties between categories

Categories

- $t\bar{t}h(b\bar{b})$ analyses based on simultaneous fit of MC to data in various categories with different # of light- and b-jets
- correlations crucial to constrain background in signal region (with multiple b-jets)

Between $t\bar{t}$+light-jet and $t\bar{t} + b$-jet categories

- uncertainties should be uncorrelated

Between sub-categories (e.g. ttb, $ttbb$, ttB)

- uncertainties should be correlated

Motivation: independent shower, matching and ME variations account for different types of uncertainties (e.g. related to collinear $g \to b\bar{b}$ splittings or hard b-production) $\Rightarrow$ no need of separate categories with uncorrelated uncertainties

Scale variations for shape (not for normalisation) uncertainties

Consider (aggressive but not fully unreasonable) *kinematic distortions* **of** $\mu_{\rm R}, \mu_{\rm F}, \mu_Q$ using various combinations of the variables

$$\mu_{\rm CMMPS} = \prod_{i=t,\bar{t},b\bar{b}} E_{T,i}^{1/4}, \qquad m_{\rm b\bar{b}}, \qquad H_{T,\rm b(t)} = E_{T,\rm b(t)} + E_{T,\rm \bar{b}(\bar{t})}, \qquad H_T = H_{T,\rm t} + H_{T,\rm b}$$

Scale	default	glo-HT	glo-Mt	glo-soft	R-Mbb	R-HTb	R-HTt	Q-CMMPS	Q-Mt
$\mu_{\rm R}$	$\mu_{\rm CMMPS}$	$H_T/2$	$m_{\rm t}$	$\mu_{\rm CMMPS}$	$(m_{\rm t} m_{\rm b\bar{b}})^{1/2}$	$\left(m_{\rm t} H_{T,\rm b}/2\right)^{1/2}$	$\left(m_{\rm t} H_{T,\rm t}/2\right)^{1/2}$	$\mu_{\rm CMMPS}$	$\mu_{\rm CMMPS}$
$\mu_{\rm F}$	$H_{T,\rm t}/2$	$H_T/2$	$m_{\rm t}$	$\mu_{\rm CMMPS}$	$H_{T,\rm t}/2$	$H_{T,\rm t}/2$	$H_{T,\rm t}/2$	$H_{T,\rm t}/2$	$H_{T,\rm t}/2$
μ_Q	$H_{T,\rm t}/2$	$H_T/2$	$m_{\rm t}$	$\mu_{\rm CMMPS}$	$H_{T,\rm t}/2$	$H_{T,\rm t}/2$	$H_{T,\rm t}/2$	$\mu_{\rm CMMPS}$	$m_{\rm t}$
Cuts	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$
ttb	0%	−41%	−27%	+4.7%	+2.3%	1.1%	−32%	−3.5%	−0.3%
ttbb	0%	−33%	−17%	−0.7%	+0.2%	3.4%	−22%	−6.4%	−1.1%
$ttbb_{100}$	0%	−29%	−13%	−9.2%	−5.6%	+2.5%	−17%	−14%	−2.9%

glo single global scale: hard, fixed and softer

R renormalisation scale (dominant!): modify or avoid b-jet dependence

Q resummation-scale (PS uncertainties): softer and fixed

Additional m_b and PDF variations with potential impact on shape (and normalisation)

	$M_b = 5.0$	$M_b = 4.5$	CTEQ 4F	MSTW_{37}	MSTW_{38}
Cuts	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$	$\Delta\sigma/\sigma$
ttb	-3.5%	$+4.4\%$	-10%	-0.1%	$+2.6\%$
$ttbb$	-0.7%	$+2.7\%$	-9.3%	$+0.2\%$	$+4.2\%$
$ttbb_{100}$	-0.1%	$+4.4\%$	-7.8%	-0.7%	$+6.9\%$

- conservative b-mass variations $m_\mathrm{b} = 4.75 \pm 0.25\,\mathrm{GeV}$ (impact on collinear regions)
- compare central MSTW to central CT10 PDF and MSTW variations with large gluon-shape distortion (MSTW eigenvector 19)

Shape variations of differential observables

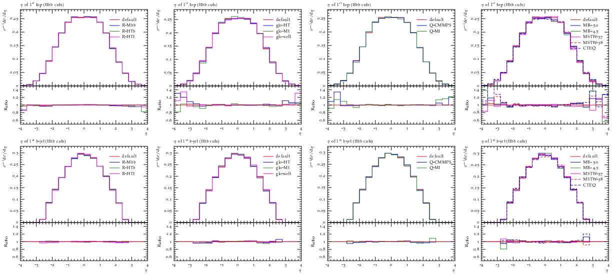
The following plots show a representative selection of shape uncertainties

- normalisation uncertainties removed by normalising all distributions to one
- columns represent (1) R-type (2) glo-type (3) Q-type (4) m_{b}+PDFs variations

Shape uncertainty of top-quark and b-jet rapidities

η_{t_1} $(ttbb)$

η_{b_1} $(ttbb)$



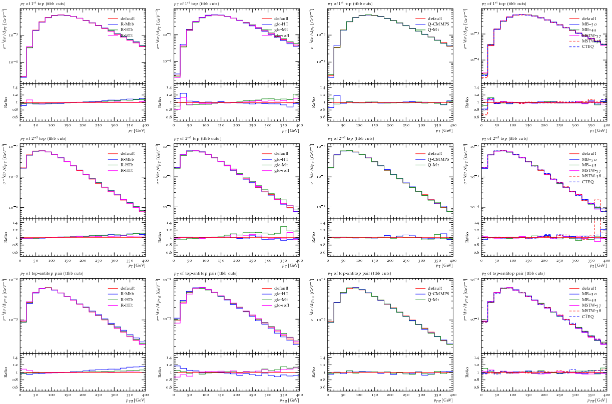
$\Rightarrow$ percent-level variations for $|\eta| < 2.5$; η_{b} very stable

Shape uncertainty of top-p_{T}

$p_{\mathrm{T},\mathrm{t}_1}$
$(ttbb)$

$p_{\mathrm{T},\mathrm{t}_2}$
$(ttbb)$

$p_{\mathrm{T},\mathrm{t}_1\mathrm{t}_2}$
$(ttbb)$



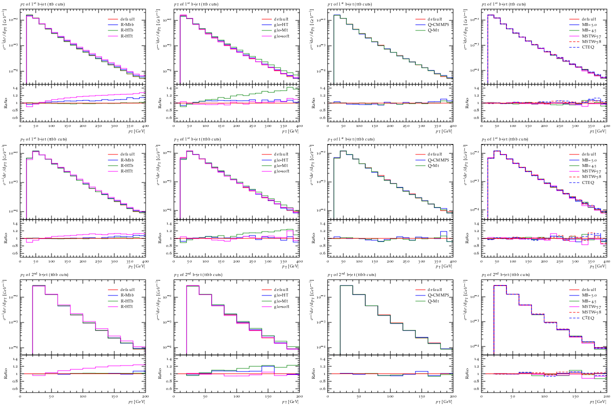
⇒ ∼10% variations (20% in the tails) driven by top-dependence of μ_{R}

Shape uncertainty of b-jet p_{T}

$p_{\mathrm{T,b_1}}$ (ttb)

$p_{\mathrm{T,b_1}}$ $(ttbb)$

$p_{\mathrm{T,b_2}}$ $(ttbb)$



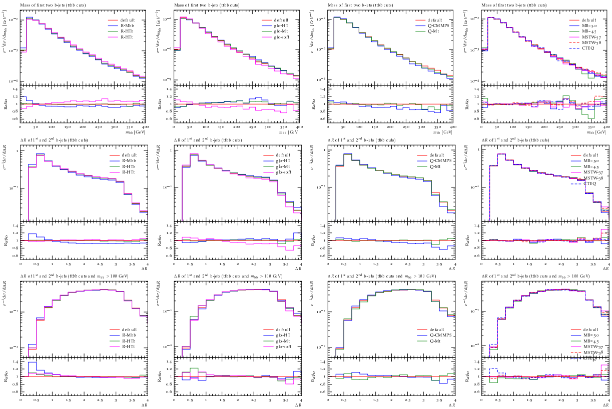
⇒ ∼10-20% variations (40% in the tails) driven by b-dependence of μ_{R}

Shape uncertainty of b-jet correlations

$m_{\mathrm{b}_1\mathrm{b}_2}$ $(ttbb)$

$\Delta R_{\mathrm{b}_1\mathrm{b}_2}$ $(ttbb)$

$\Delta R_{\mathrm{b}_1\mathrm{b}_2}$ $(ttbb_{100})$

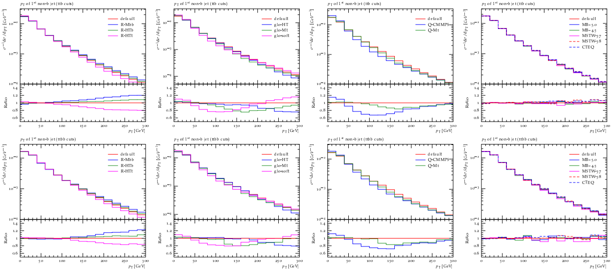


⇒ ∼10-20% variations driven by b-dependence of μ_{R} (at small m_{bb} and ΔR) and (agressive) reduction of μ_Q in the tail

Shape uncertainty of 1^{st} light-jet p_{T}

p_{T,j_1} (ttb)

p_{T,j_1} $(ttbb)$



⇒ up to ∼30% variations at intermediate p_{T} values. Indicates that the considered variations (dominated by choice of soft resummation scale) are (probably too) conservative

Scale choices (YR4) and uncertainties (no proposal yet)

Factorisation (μ_Q) and resummation (μ_Q) scales

$$E_{T_i} = \sqrt{m_i^2 + p_{T,i}^2}$$

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

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