$t\bar{t}H$ theory activities

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on behalf of the ttH conveners

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Foreword

- after YR4 we decided to focus $t\bar{t}H/tH$ subgroup activities on highest priority TH issues in EXP analyses
- in the recent months we focussed on TH uncertainties of $t\bar{t}+b$-jet background to $t\bar{t}H(b\bar{b})$: a very serious bottleneck of $t\bar{t}H(b\bar{b})$ searches!
- modern tools support automated $t\bar{t}b\bar{b}$ simulations, but $t\bar{t}b\bar{b}$ remains a highly nontrivial multi-particle multi-scale QCD process . . .
- . . . understanding of $t\bar{t}b\bar{b}$ QCD dynamics crucial to assess TH uncertainties

Outline

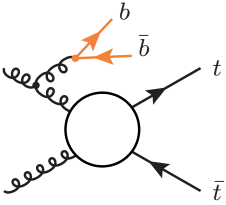
1. 5F vs 4F scheme for $t\bar{t} + b$-jets at NLO

2. $t\bar{t}b\bar{b}$ MC comparisons and open issues

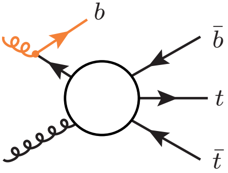
3. New Powheg 4F generator for $t\bar{t} + b$-jets

Option 1: NLOPS $t\bar{t}$ 5F (e.g. Powheg's hvq generator)

$t\bar{t}b\bar{b}$ 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 (parton shower allows for accurate tuning to data)

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

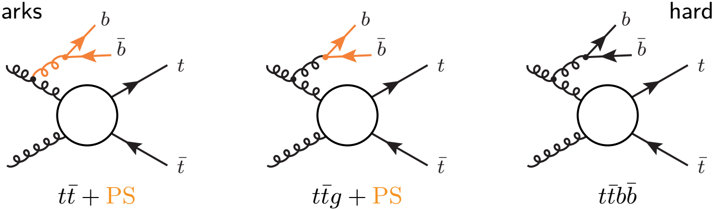
- crucial for more realistic TH uncertainties

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

softer b-quarks $\Longleftarrow$

harder b-quarks $\Longrightarrow$



Precision and CPU cost strongly depend on choice of merging cut $Q_{\rm cut}$

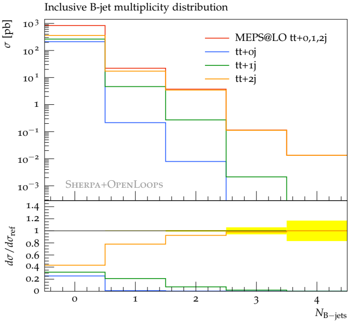
- separates ME regions ($k_T > Q_{\rm cut}$) from shower regions ($k_T < Q_{\rm cut}$)

Does this describe $t\bar{t}$+b-jet production mostly through $t\bar{t}b\bar{b}$ MEs?

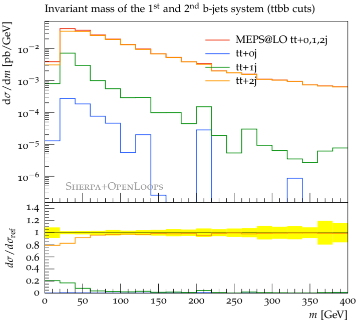
Amount of $t\bar{t}$+jets ME information

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

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



m_{bb} with ttbb cuts



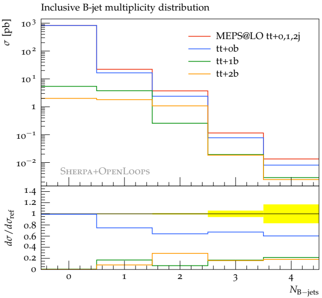
Observables with ≥ 1 additional b-jets

- dominated by $t\bar{t} + 2$ jet MEs (suggesting ME precision) ...

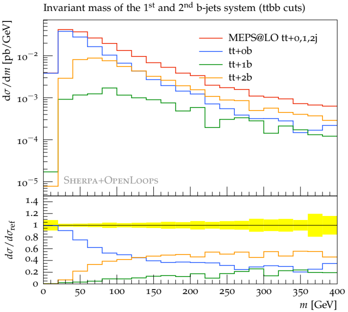
Amount of $t\bar{t} + b$-jets ME information

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

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



m_{bb} with ttbb cuts

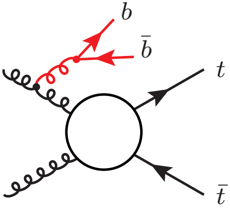


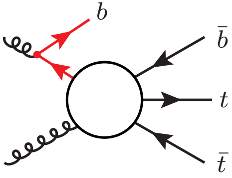
Observables with ≥ 1 additional b-jets

- actually dominated by MEs with 2 light jets and no b-jets (up to $Q \sim 100\,\mathrm{GeV}$)!

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

$t\bar{t}b\bar{b}$ 4F at NLO





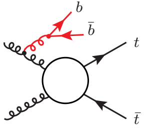
4F $t\bar{t}b\bar{b}$ MEs with $m_b > 0$ cover full b-quark phase space

- NLO precision for $t\bar{t} + 2\,b$-jet and $1\,b$-jet! [Cascioli et al '13]
- 80% LO uncertainty reduced to 20–30% at NLO
- collinear $g \to b\bar{b}$ splittings and m_b effects very important

what about drawbacks of 4F scheme (e.g. no b-quark PDF)?

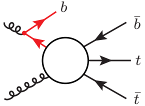
Dominant topologies in 4F $t\bar{t}b\bar{b}$ (FS vs IS $g \to b\bar{b}$)

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



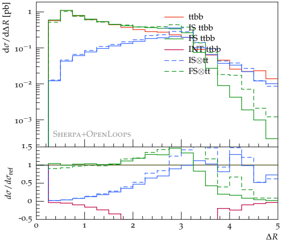
- dominant in full ttbb and ttb phase space
- notion of $g \to b\bar{b}$ splittings and IS/FS separation seems ill defined at large ΔR_{bb}, m_{bb}, $p_{T,b}$ due to sizable interferences

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

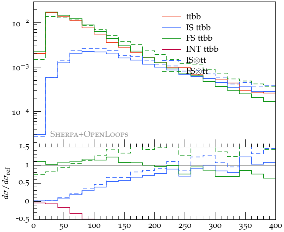


- mostly clearly subdominant (no need for 5F scheme resummation)

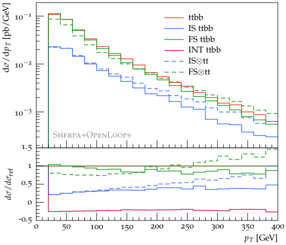
ΔR_{bb} with ttbb cut



m_{bb} with ttb cuts

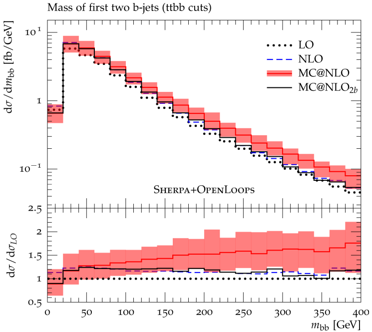


p_{T,b_1} with ttb cuts



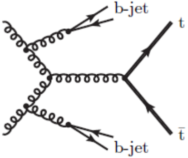
supports choice of 4F scheme with $m_b > 0$ and no b-quark PDF

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



Main NLOPS features to keep in mind

- similarly mild NLO K-factors for ttbb and ttb observables
- large matching/shower effects in Higgs region ($\sim$ 30%)
- due to double $g \to b\bar{b}$ splittings (one splitting from PS!)



⇒ TH uncertainties related to matching & shower crucial!

Outline

Tuned comparison of NLO+PS $t\bar{t}b\bar{b}$ simulations at 13 TeV

Different NLOPS methods, showers, and m_b treatments

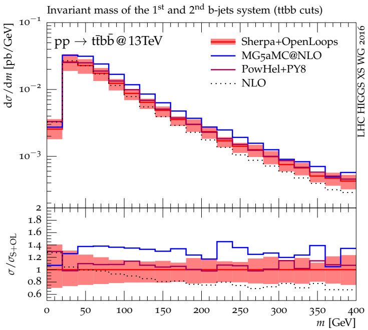
Tool	Matching	Shower	m_b[GeV]	gencuts
SHERPA2.1+OPENLOOPS	SMC@NLO	Sherpa 2.1	4.75 (4F)	no
MG5_aMC@NLO	MC@NLO	Pythia 8.2	4.75 (4F)	no
POWHEL	Powheg	Pythia 8.2	0 (5F)	$p_{T,b} > 4.75\,\text{GeV}$ $\frac{m_{bb}}{2} > 4.75\,\text{GeV}$

note: heuristic implementation of m_b effects in Powhel

Main idea: NLOPS parton level w.o. top decays and hadronisation

- transparent picture of key QCD dynamics and uncertainties
- bias from neglecting hadronisation effects is relatively small in Sherpa/MG5 comparison and zero in Powhel+PY8/MG5+PY8 comparison (see backup slides)

$t\bar{t}b\bar{b}$ distributions with $\geq 2b$-jets



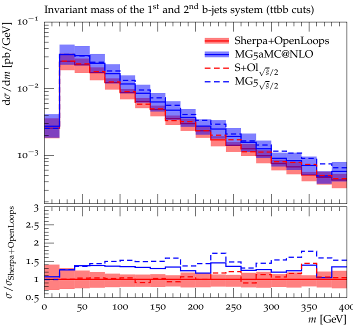
Sherpa+OpenLoops vs PowHel+PY8

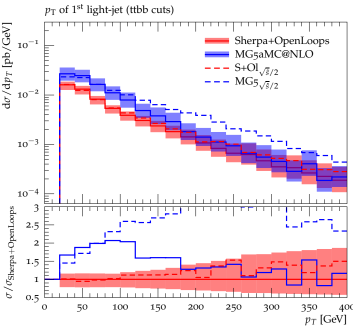
- well consistent also in observables that receive significant shower corrections
- confirmation of "double-splitting effects" (see e.g. m_{bb})

Sherpa+OpenLoops vs MG5aMC@NLO

- 40% enhancement of $t\bar{t} + 2$b XS & sizable differences in NLO radiation pattern
- related to strong sensitivity to resummation scale (shower starting scale) in MG5 . . .

Dependence on resummation scale μ_Q





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.

Outline

$t\bar{t}b\bar{b}$ 4F with Powheg+OpenLoops [Jezo, Lindert, S.P., in preparation]

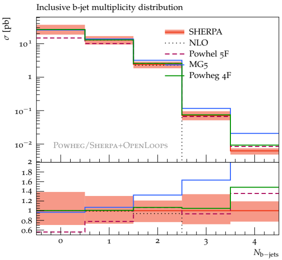
First $t\bar{t}b\bar{b}$ 4F Powheg simulation with $m_b > 0$

- consistent comparison against Sherpa+OpenLoops and MG5aMC@NLO possible

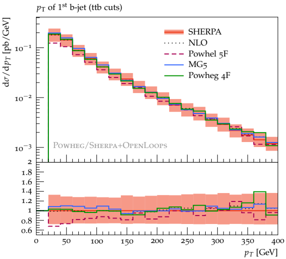
NLOPS Powheg+PY8 results with YR4 settings (preliminary)

- improved agreement with NLO wrt Powhel (especially for ttb cuts)
- good agreement with Sherpa with $ttbb$ and ttb cuts
- confirms tension with MG5 with $ttbb$ cuts

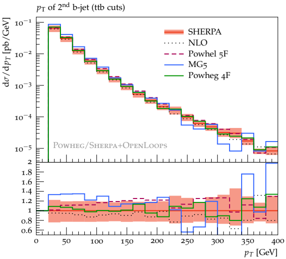
$N_{b\,\mathrm{jets}}$



p_{T,b_1} with ttb cuts*



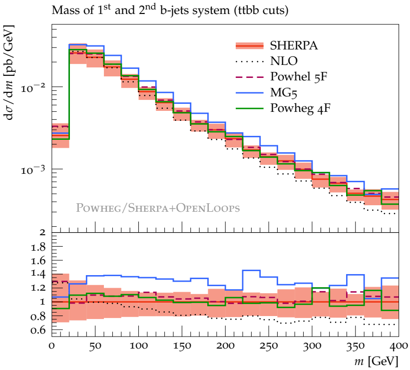
p_{T,b_2} with ttbb cuts



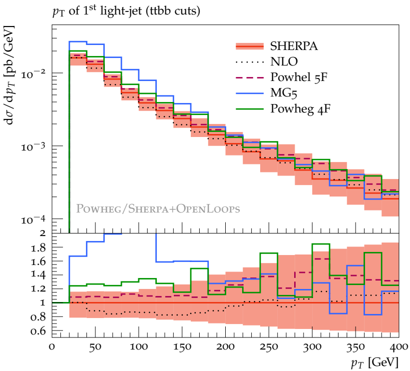
*note excellent consistency of all NLOPS 4F predictions with ttb cuts

Further Powheg+PY8 results

m_{bb} with ttbb cuts



p_{T,j_1} with ttbb cuts

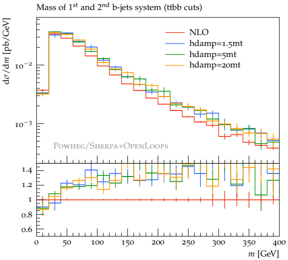


- "double $g \to b\bar{b}$ splittings" confirmed also by Powheg+PY8

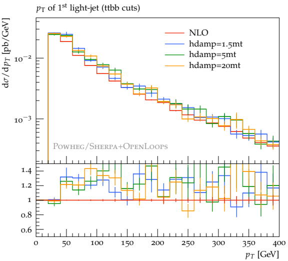
- Powheg+PY8 features enhancement in same direction as MG5+PY8
- but no strong distortion of spectrum

Stability of Powheg+PY8 wrt hdamp (very preliminary)

m_{bb} with ttbb cuts



p_{T,j_1} with ttbb cuts



Idea: compare hdamp in Powheg vs μ_Q in MC@NLO

- since both scales used to separate 1st emission into hard region (LO ME) and soft region (Sudakov resummation + local K-factor)

Weak hdamp dependence in Powheg+PY8

- probably because 1st Powheg emission 100% from ME (which also dictates scalup!)

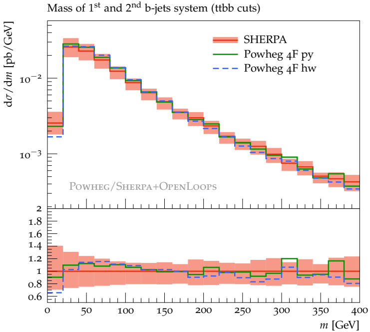
Strong μ_Q dependence in MG5aMC@NLO+PY8

- probably because 1st MC@NLO emission matched to PY8 below μ_Q=scalup

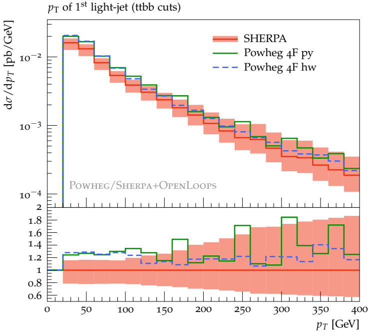
⇒ matching or PY8 issue? (cf. small μ_Q dependence in Sherpa)

Shower dependence of Powheg 4F (very preliminary)

m_{bb} with ttbb cuts



p_{T,j_1} with ttbb cuts



⇒ Negligible difference between Powheg+Pythia 8.2.1.0 vs Powheg+Herwig 7.1.0*

*Pythia with YR4 settings; Herwig with angular ordering and default settings (apart from YR4 top/bottom masses and PDFs)

Conclusions and Outlook

NLOPS simulations of $t\bar{t}+b$-jet production

- 4F scheme preferable since less sensitive to $g \to b\bar{b}$ splittings wrt 5F
- YR4 MC comparisons have revealed significant matching/shower dependence
- reliable estimate of TH uncertainty requires further in-depth studies (ongoing)
- can now be addressed with three independent $t\bar{t}b\bar{b}$ 4F generators: Sherpa, MG5aMC@NLO, Powheg (new!)

Todo: realistic estimates of $t\bar{t}b\bar{b}$ MC uncertainties in EXP analyses

- require extension of MC studies to particle level and detailed framework for TH uncertainties (matching, shower, hadronisation, . . .)
- try to exploit possible sinergies between $t\bar{t}H$ and $t\bar{t}b\bar{b}$ measurements

Todo: identify and address further TH priorities in $t\bar{t}H/tH$ searches

- $t\bar{t}H(WW)$ backgrounds (and signal modelling)?

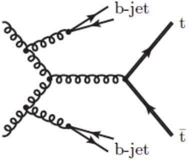
Backup slides

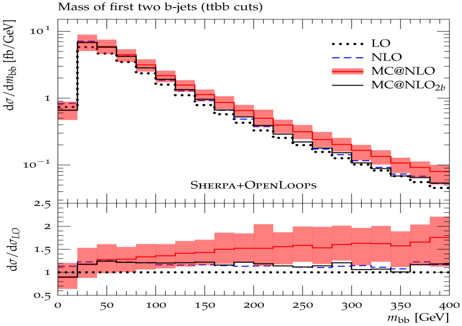
NLOPS $t\bar{t}b\bar{b}$ 4F with SHERPA+OPENLOOPS [Cascioli et al '13]

Convergence of 4F scheme but unexpected MC@NLO enhancement

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

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

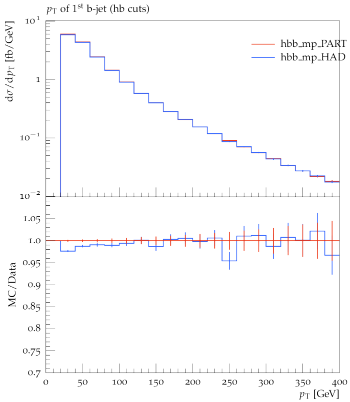
Possible bias of MC comparisions?

- 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

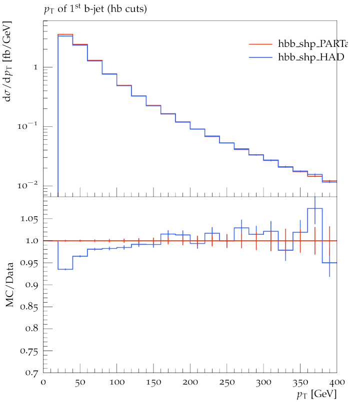
see https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LOpphHadronisation

Hadronisation corrections in MG5+PY8 vs Sherpa2.1

MG5+Pythia 8.2



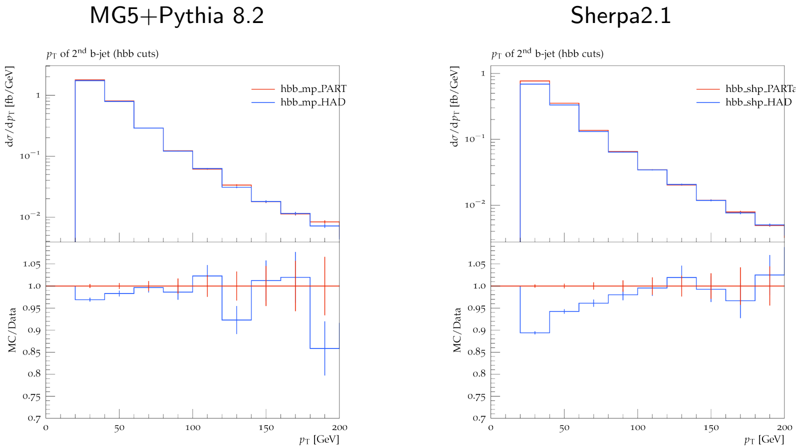
Sherpa2.1



p_T of leading b-jet in $H+\geq 1b$ selection

- moderate hadronisation corrections (up to 6%) in the soft region
- differences below 3–4%

Hadronisation corrections in MG5+PY8 vs Sherpa2.1



p_T of 2nd b-jet in $H+\geq 2b$ selection

- hadronisation corrections up to 10% in the soft region
- differences up to 7%

Combination of $t\bar{t}+X$ and $t\bar{t}b\bar{b}$ MC samples

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

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

$\Rightarrow$ 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

$\Rightarrow$ 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

$t\bar{t}b\bar{b}/t\bar{t}+X$ combination: refinement at 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 ⇔ normalisation
- "kinematic" variations of μ_R, μ_F, μ_Q ⇔ shape
- variations of μ_Q in MC@NLO and h_{damp} in Powheg ⇔ 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