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

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based on


and HXSWG studies in collaboration with


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Foreword 1

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

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

$\Rightarrow$ 10% level precision

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

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

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

$\bar{b}g \to t\bar{t}b$ + 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**

$\Rightarrow$ 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

$\iff$

harder $b$-quarks

$t\bar{t} + PS$

$t\bar{t}g + PS$

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

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

- $k_T$-resolution cut separates MEs (with $m_b = 0$) from shower (collinear approx.)

- $g \rightarrow b\bar{b}$ 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

Invariant mass of the 1st and 2nd b-jets system (ttbb cuts)
Option 3: NLOPS $t\bar{t}b\bar{b}$ in 4F scheme

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

- MEs cover full $b$-quark phase space including IS and FS $g \rightarrow b\bar{b}$ 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 $g \rightarrow b\bar{b}$ splittings (in ttbb and ttb phase space)
- negligible $g \rightarrow b\bar{b}$ fragmentation logs beyond NLO at $p_T \lesssim 50–100$ GeV

[Cascioli et al '13]
Nontrivial features of $pp \rightarrow t\bar{t}b\bar{b}$ 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 $g \rightarrow b\bar{b}$ splittings [Cascioli et al. '13]

$\Rightarrow$ crucial to understand $g \rightarrow b\bar{b}$ splittings and matching+shower uncertainties
YR4 comparisons of NLOPS $\bar{t}b\bar{b}$ generators [1610.07922]

**MG5aMC@NLO+PY8 (4F) vs Sherpa (4F)**
- 40% NLOPS/NLO enhancement of $\bar{t}t + 2b$ XS in MG5
- related to sizeable enhancement of NLO radiation at $p_T \sim 100$ 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 $g \rightarrow b\bar{b}$ splittings (ad-hoc cuts)

**Question:** small theory uncertainty or accidental?
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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 $\alpha_S^{LO}$ for $\sigma_{LO}$ (typical in $t\bar{t}b\bar{b}$ literature) $\Rightarrow \sigma_{NLO}/\sigma_{LO} \sim 1.2$
- using $\alpha_S^{NLO}$ throughout $\Rightarrow \sigma_{NLO}/\sigma_{LO} \sim 1.9$ 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”)

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

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

$\Rightarrow$ high stability wrt $h_{damp}$ variations for multiscale process
NLOPS vs NLO Powheg $t\bar{t}b\bar{b}$ predictions [1802.00426]

\[ N_b \]

Inclusive b-jet multiplicity distribution

\[ M_{b_1 b_2} \]

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

\[ p_{T,j_1} \]

$\rho$ of 1st light-jet (ttbb cuts)

**Moderate NLOPS/NLO corrections**

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

**Shape of light-jet $p_T$**

- NLOPS quite similar to fixed-order NLO
- LOPPS/NLOPS indicates that PY8 can strongly overestimate radiation at $p_T \sim 200$ GeV (see YR4) but Powheg+PY8 spectrum is NLO-like
Matching+shower uncertainties of Powheg $t\bar{t}b\bar{b}$ [1802.00426]

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

- Inclusive b-jet multiplicity distribution
- Invariant mass of the 1st and 2nd b-jets system ($t\bar{t}b\bar{b}$ cuts)
- $p_T$ of 1st light-jet ($t\bar{t}b\bar{b}$ cuts)

Powheg+PY8 vs Herwig7

- MC uncertainties $\ll$ 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 $h_{\text{bzd}}$ restriction and independence of 1st Powheg emission wrt parton shower
Variations of $g \rightarrow b\bar{b}$ splittings + choice of $\alpha_S$ + scalup in PY8

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

- double-splitting effects stable wrt variations of $g \rightarrow b\bar{b}$ 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

<table>
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<tr>
<th>Tool</th>
<th>MC@NLO</th>
<th>Powheg</th>
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<th>Herwig</th>
<th>Sherpa</th>
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<td>T. Jezo, J. Lindert</td>
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Plan and philosophy for theoretically consistent tool comparison

- coherent definition of intrinsic MC uncertainties across different tools: separate, 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

⇒ 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

\[
\frac{d\sigma}{d\Phi_B} = \left[ B(\Phi_B) + V(\Phi_B) + \int d\Phi_1 R_{\text{soft}}(\Phi_B, \Phi_1) \right] \left[ \Delta(t_{IR}) + \Delta(k_T) \frac{R_{\text{soft}}(\Phi_R)}{B(\Phi_B)} d\Phi_1 \right] =: \tilde{B}_{\text{soft}}(\Phi_B) \supset \text{integrated soft radiation} + \int d\Phi_1 R_{\text{soft}}(\Phi_R) - R_{\text{soft}}(\Phi_R) \] d\Phi_1 \text{ remnant hard radiation}

Powheg vs MC@NLO difference only in \( R_{\text{soft}} \)

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

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

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

\Rightarrow \text{ choose } h_{\text{damp}} = \mu_Q \text{ and } g_{\text{soft}} \text{ as similar as possible for consistent comparison}
MC comparison with $t\bar{t} + 2b$ cuts

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 light-jet radiation spectrum (normalised to Sherpa YR4)

Current interpretation

\[ \frac{{\bar{B}}_{\text{soft}}}{B} \sim \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}} \sim 2 \]

⇒ 100% distortion of jet-\( p_T \) spectrum

\[ \frac{d\sigma}{d\Phi_Bd\Phi_1} = R + \left[ \frac{{\bar{B}}_{\text{soft}}}{B} \Delta - 1 \right] R_{\text{soft}} \]

≥ 100% instead of \( \mathcal{O}(\alpha_S) \)

⇒ effect of hard-jet recoil on \( p_T \) of soft \( b \)-jets induces \( N_b \)-bin migrations

⇒ enhancement of \( tt + 2b \) cross section

Depends on relative importance of soft/hard contributions
Soft/hard separation

Natural kinematic separation of $\sigma_{ttbb}^{NLO}$

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

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

Technical separation in NLOPS tools

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

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
Convergence of 4F scheme but unexpected MC@NLO enhancement

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<td>$463.3^{+66%+15%}_{-36%-12%}$</td>
<td>$123.4^{+63%+17%}_{-35%-13%}$</td>
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<td>$\sigma_{NLO}$ [fb]</td>
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<td>1.07</td>
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Large enhancement ($\sim 30\%$) in Higgs region from double $g \rightarrow b\bar{b}$ splittings

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

⇒ TH uncertainties related to matching, shower and 4F/5F schemes crucial!
Missing large logarithms from $g \rightarrow b \bar{b}$ fragmentation? I

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

\[
\rho(Q^2, K^2) = \int_{2m_b}^{Q} dK \, P_{g \rightarrow b\bar{b}}(K) \times n_g(Q^2, K^2)
\]

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

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

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

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

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

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

with double logarithms $L = \ln(K^2/Q^2)$
Missing large logarithms from $g \to b\bar{b}$ fragmentation? II

**Distribution** $d\rho(Q^2, K^2)/dK$ 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**

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$t\bar{t}b\bar{b}$ 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 $\Delta R_{bb}$, $m_{bb}$, $p_T^{b}$ 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)

$\Delta R_{bb}$ 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

$N_b$

Inclusive b-jet multiplicity distribution

$M_{b_1b_2}$

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

$p_{T,j_1}$

$p_T$ of 1st light-jet (ttbb cuts)

**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

**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, however 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

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

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
  - $\Phi_B \rightarrow \Phi_R$ FKS mappings $\Rightarrow b\bar{b}$ system absorbs jet recoil and becomes much softer
  - $R(\Phi_R)$ enhancement that violates $ttbb$ factorisation

- similar issues expected also in MC@NLO matching

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

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

$\Rightarrow$ high stability wrt $h_{\text{damp}}$ variations
Nominal MG5_aMC and Sherpa+OpenLoops predictions in YR4

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

$\mu_Q$ variations enhance the discrepancy

- $\mu_Q = \sqrt{s}/2$ in Sherpa to mimic MG5_aMC default choice $0.1 < f(\xi) < 1$
- strong $\mu_Q$-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 $\hat{s} \rightarrow H_T$ 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 $\sigma_H$ in MC@NLO

$$\frac{d\sigma}{d\Phi_B} = \tilde{B}_{\text{soft}}(\Phi_B) \left[ \Delta(t_{IR}) + \Delta(k_T) K_{\text{soft}}(\Phi_1) d\Phi_1 \right] + \left[ R(\Phi_R) - B(\Phi_B) K_{\text{soft}}(\Phi_1) \right] d\Phi_1$$

S–events (LHE×shower)

H–events

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

$$R(\Phi_R) \rightarrow B(\Phi) K_{\text{soft}}(\Phi_1) = B(\Phi) K_{\text{shower}}(\Phi_1) g_{\text{soft}}(\Phi_1, \mu_Q)$$

and integrated out in

$$\tilde{B}_{\text{soft}}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + B(\Phi_B) \int d\Phi_1 K_{\text{soft}}(\Phi_1)$$

Matching distorted by $K$-factor $\tilde{B}_{\text{soft}}/B \gtrsim 2$ and $(R - B K_{\text{soft}}) < 0$

$$\frac{d\sigma}{d\Phi_B d\Phi_1} = R + \left[ \frac{\tilde{B}_{\text{soft}}}{B} \Delta - 1 \right] B K_{\text{soft}} = \left( \frac{\tilde{B}_{\text{soft}}}{B} \Delta \right) R + \left[ \frac{\tilde{B}_{\text{soft}}}{B} \Delta - 1 \right] (B K_{\text{soft}} - R)$$

$\gtrsim 100\%$distortion

$\gtrsim 100\%$max resummation

$>0$

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

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

- $p_T$(jet) < $k_T(g \rightarrow b\bar{b})$ ⇒ soft
- $p_T$(jet) > $k_T(g \rightarrow b\bar{b})$ ⇒ hard

- 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**

- **Powhe**: $S$-contribution $\sim 50\%$, i.e. comparable to $k_T(b\bar{b}) < p_T(jet)$ (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

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

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

- top decays are trivial (well understood EW interactions) but render the analysis of $b$-quark production in $WWWb\bar{b}b\bar{b}$ final states quite cumbersome

- switching off top decays is very useful in order to investigate the QCD dynamics of $b$-production in $pp \rightarrow t\bar{t}b\bar{b}$ (which dominates TH uncertainties!)

- since top quarks carry SU(3) charge, also hadronisation needs to be switched off

Possible bias of MC comparisons?

- 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/L0pphHadronisation
NLOPS/NLO and $\mu_Q$, hdamp dependence

- **$N_b$**: Inclusive B-jet multiplicity distribution
- **$M_{b_1 b_2}$**: Invariant mass of the 1st and 2nd b-jets system (ttbb cuts)
- **$pT_{j_1}$**: $p_T$ of 1st light-jet (ttbb cuts)

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