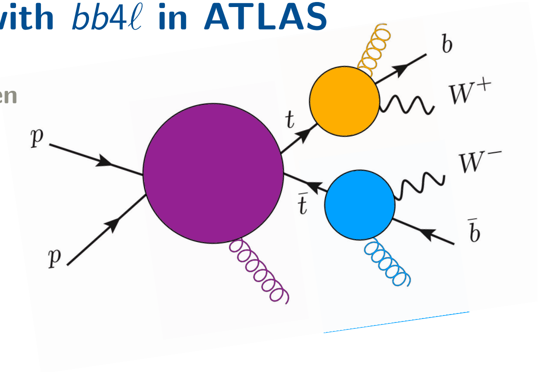
Katharina Voß

Modelling $b\bar{b}\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$ with $bb4\ell$ in ATLAS

Beyond Flavour Workshop, Siegen

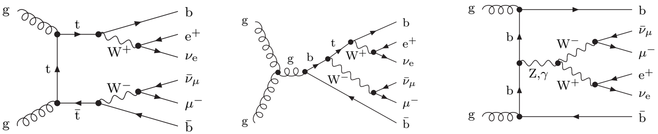
24th June 2025



What is the $bb4\ell$ simulation?

→ process implemented in the POWHEG-BOX-RES, which describes *WWbb* in dileptonic decay[1] **which can be interfaced with a parton shower**

Includes double-, single- and non-resonant diagrams:

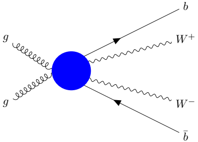


+ corresponding NLO corrections

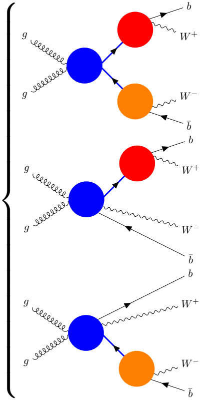
[1]different flavour, local code modification in athena to allow same flavours
→ ATLAS also requested to merge change in official [$bb4\ell$-dl/-sl beta git-repo]

Resonance history projectors

Output from ***bb4ℓ*** **ME calculation:** initial state + $b\bar{b}\ell^+\nu_\ell\ell^-\bar{\nu}_\ell$ final state
→ no information about intermediate resonances
→ technical issues in POWHEG generation
+ recoil distorts invariant mass of resonances in PS



$$\rightarrow \begin{cases} |\mathcal{M}^{\mathrm{LO}}_{t\bar{t}}|^2 \\ |\mathcal{M}^{\mathrm{LO}}_{tW\bar{b}}|^2 \\ |\mathcal{M}^{\mathrm{LO}}_{\bar{t}Wb}|^2 \end{cases} \rightarrow$$



Planned study: Alternative resonance projectors

Explicitly, different $t\bar{t}$ projector: $|\mathcal{M}^{\mathrm{LO}}_{t\bar{t}}|^2 \rightarrow |\mathcal{M}^{\mathrm{LO}}_{WWbb}|^2 - |\mathcal{M}^{\mathrm{LO}}_{tW\bar{b}}|^2 - |\mathcal{M}^{\mathrm{LO}}_{\bar{t}Wb}|^2$

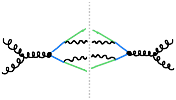
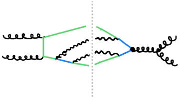
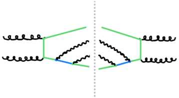
Outline

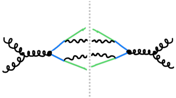
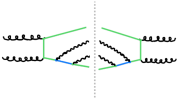
- **Improvements in $bb\ell\ell\nu\nu$ modelling with $bb4\ell$**
- **Usage of resonance histories in $bb4\ell$ events**
- **The `allrad` multiple radiation scheme**

Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

- correct treatment of $t\bar{t}/tW$ interference at NLO

 $+\,2\mathrm{Re}$  $+$ 

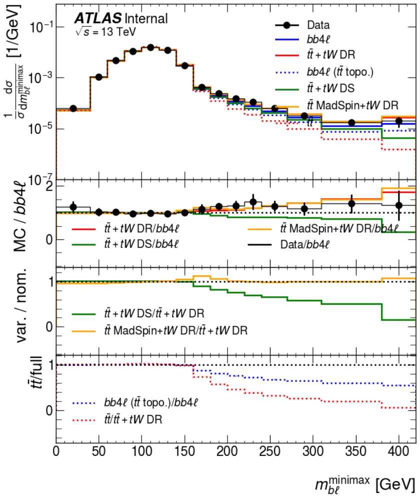
instead of  $+$  ($t\bar{t} + tW$ DR)

- off-shell effects accurate at NLO
- top decay description at NLO

Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

- correct treatment of $t\bar{t}/tW$ interference at NLO



Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

- correct treatment of $t\bar{t}/tW$ interference at NLO $\rightarrow$ tW **DR/DS uncertainty removed**
- off-shell effects accurate at NLO
- top decay description at NLO

Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

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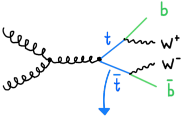
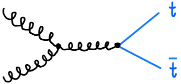


full top quark propagator

instead of



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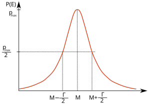


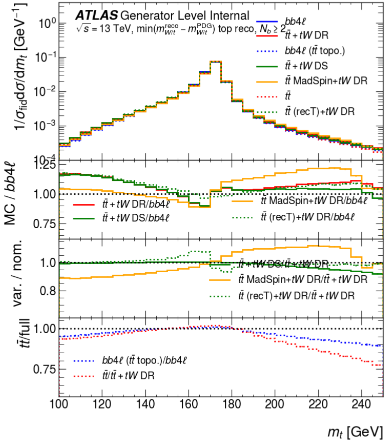
Breit-Wigner

- top decay description at NLO

Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

- correct treatment of $t\bar{t}/tW$ interference at NLO → **DR/DS uncertainty removed**
- off-shell effects accurate at NLO



Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

- correct treatment of $t\bar{t}/tW$ interference at NLO $\rightarrow$ **DR/DS uncertainty removed**
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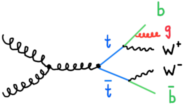

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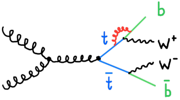
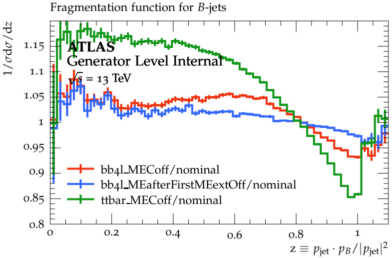


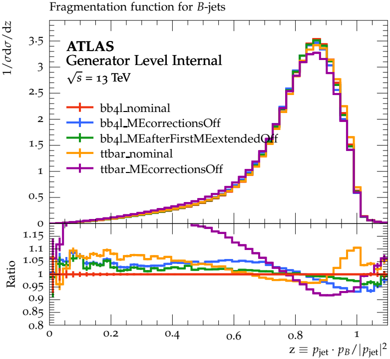
instead of LO top decay

Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

- correct treatment of $t\bar{t}/tW$ interference at NLO → **DR/DS uncertainty removed**
- off-shell effects accurate at NLO → **line shape uncertainty removed**
- top decay description at NLO
  → discussed in [$bb4\ell$-dl/sl paper]





→ plots with old $bb4\ell$ process version

Modelling improvements through $bb4\ell$

Improvements through $bb4\ell$ compared to $t\bar{t} + tW$

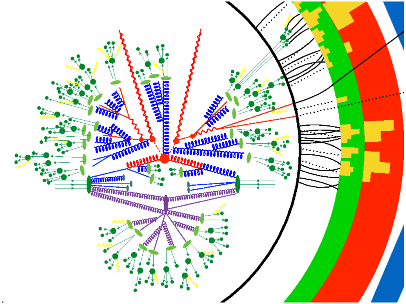
- correct treatment of $t\bar{t}/tW$ interference at NLO $\rightarrow$ **DR/DS uncertainty removed**
- off-shell effects accurate at NLO $\rightarrow$ **line shape uncertainty removed**
- top decay description at NLO

To use $bb4\ell$ as a nominal MC sample, we need to generate and check the associated modelling uncertainties

Overview of $bb4\ell$ modelling uncertainties

Uncertainties in

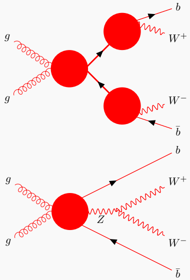
- **Powheg hard process**
  - μ_R, μ_F scale variation
  - PDF uncertainties
  - h_{damp}
  - $bb4\ell$: α_S in Powheg Sudakov
  - $bb4\ell$: inverse width correction
- **Powheg-Pythia8 matching**
  - $p_{\mathrm{T}}^{\mathrm{hard}}$ variation
  - $bb4\ell$: scale resonance veto
- **Pythia8 parton shower**
  - A14 Var1 tune variations (underlying event variation)
  - Colour reconnection
  - Pythia8 splitting kernel variations (μ_R and c_{NS})
  - Recoil uncertainty
  - Alternative parton shower: Herwig7



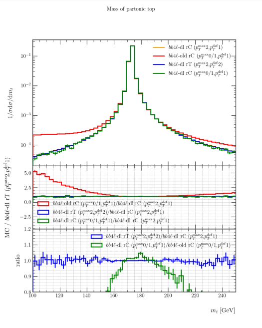
Resonance histories: partonic top-quark

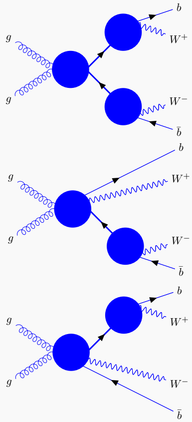
Different resonance histories in previous $bb4\ell$ and new $bb4\ell$-dl

$\rightarrow$ what can we do with new $t\bar{t}$, tW and $\bar{t}W$ resonance histories?



[previous $bb4\ell$]

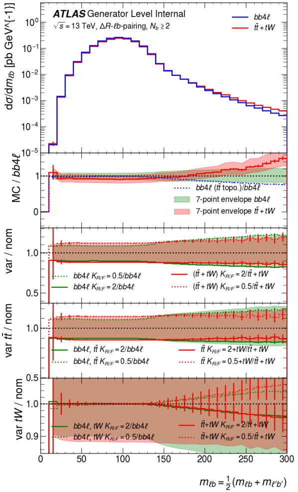




[new $bb4\ell$-dl]

Resonance histories: ME scale variations

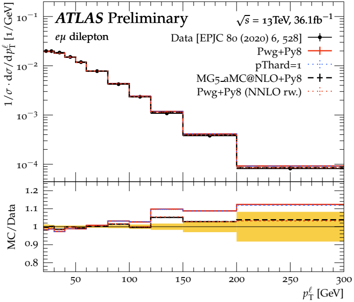
Can we vary the ME scale independently in $t\bar{t}$ and tW projected resonance histories in $bb4\ell$?

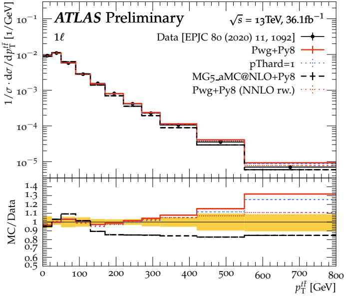


- $t\bar{t}$ resonance histories:
  $\mu_0 = [(m_t^2 + p_{T,t}^2)(m_t^2 + p_{T,\bar{t}})^2]^{1/4}$
- $tW^-\bar{b}$ resonance histories:
  $\mu_0 = [(m_t^2 + p_{T,t}^2)(m_{\bar{b}}^2 + p_{T,\bar{b}})^2]^{1/4}$

Resonance histories: Higher-order $t\bar{t}$ reweighting

Can we reweight partonic $t\bar{t}$ distributions to higher order on-shell $t\bar{t}$ predictions?



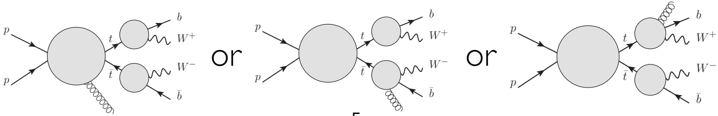


[ATL-PHYS-PUB-2023-029]

→ reweighting partonic top-quark distributions to NNLO QCD + NLO EW $t\bar{t}$ predictions [hep-ph/1705.04105] (top p_T, $m_{t\bar{t}}$) + ($t\bar{t}$ p_T with MATRIX software)

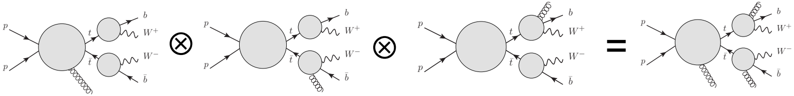
Multiple radiation scheme

Usual POWHEG radiation scheme → keep only hardest emission (usually from production)



$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \left[\Delta(q_{\text{cut}}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)}\, d\Phi_{\text{rad}} \right]$$

Multiple radiation scheme (`allrad`) → merge emissions into single event with multiple emissions



$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \prod_{\alpha=\alpha_b,\alpha_{\bar{b}},\alpha_{\text{ISR}}} \left[\Delta_\alpha(q_{\text{cut}}) + \Delta_\alpha(k_T^{\alpha}) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi_{\text{rad}}^{\alpha}))}{B(\Phi_B)}\, d\Phi_{\text{rad}}^{\alpha} \right]$$

Illustration taken from [J.M. Lindert, QCD@LHC]

→ differences in NLO+PS matching in $t\bar{t}$ and $bb4\ell$

+ need to check that everything works technically with new LHE format (e.g. Pythia8 recoil-to-top)

Dedicated $bb4\ell$ parton shower matching

$t\bar{t} \rightarrow$ emission only from the production process

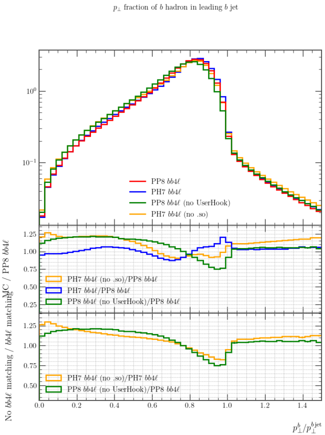
$bb4\ell \rightarrow$ merge emissions into single event with multiple emissions

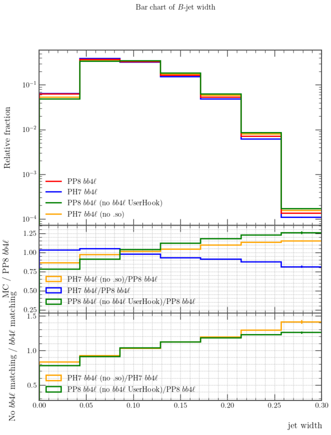
$\rightarrow$ parton shower generates emissions with $k_T < k_T^\alpha$, k_T^α, $\alpha \in \{\text{ISR}, \bar{b}, b\}$

- Emissions from production process: main31 (the same for $t\bar{t}$ and $bb4\ell$)
- Emissions from decay process: [dedicated $bb4\ell$ UserHook (Py8)] or [shared library (H7)]

$\rightarrow$ some differences in the modelling systematics between $t\bar{t}$ and $bb4\ell$ could be due to different generation method

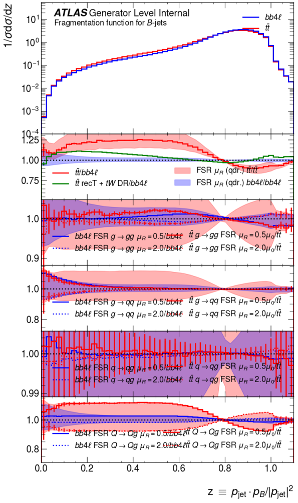
Influence of dedicated $bb4\ell$-PS matching





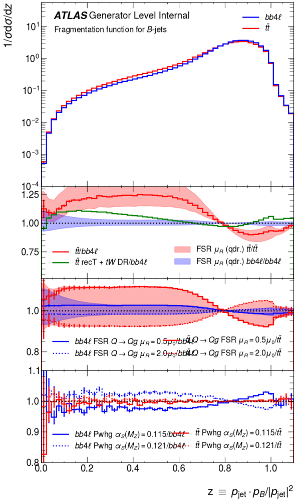
→ consistent behaviour when applying or not applying dedicated $bb4\ell$ matching in Py8 and H7
→ no dedicted $bb4\ell$ matching: more PS radiation off of b-quark, less hard B-hadrons and broader b-jets

$bb4\ell$ systematics: FSR μ_R and α_S in Powheg Sudakov



$\rightarrow$ reasonable agreement of all μ_R splitting kernel variations except for $Q\rightarrow Qg$ splitting kernel ($Q\in\{b,t\}$)
Possible explanation: first emission from top-quark decay already done by POWHEG (NLO top decay description in $bb4\ell$)

$bb4\ell$ systematics: FSR μ_R and α_S in Powheg Sudakov



→ same influence of all μ_R splitting kernel variations except for $Q \to Qg$ splitting kernel ($Q \in \{b, t\}$)
Possible explanation: first emission from top-quark decay already done by POWHEG (NLO top decay description in $bb4\ell$)
→ vary α_S in Powheg Sudakov (by using PDF set with different $\alpha_S(M_Z)$ value) [hep-ph/1801.03944]

Open Questions

Alternative resonance history projectors

Check influence of alternative $t\bar{t}$ resonance history projector, when available
$|\mathcal{M}^{\mathrm{LO}}_{t\bar{t}}|^2 \rightarrow |\mathcal{M}^{\mathrm{LO}}_{WWbb}|^2 - |\mathcal{M}^{\mathrm{LO}}_{tW\bar{b}}|^2 - |\mathcal{M}^{\mathrm{LO}}_{\bar{t}Wb}|^2$

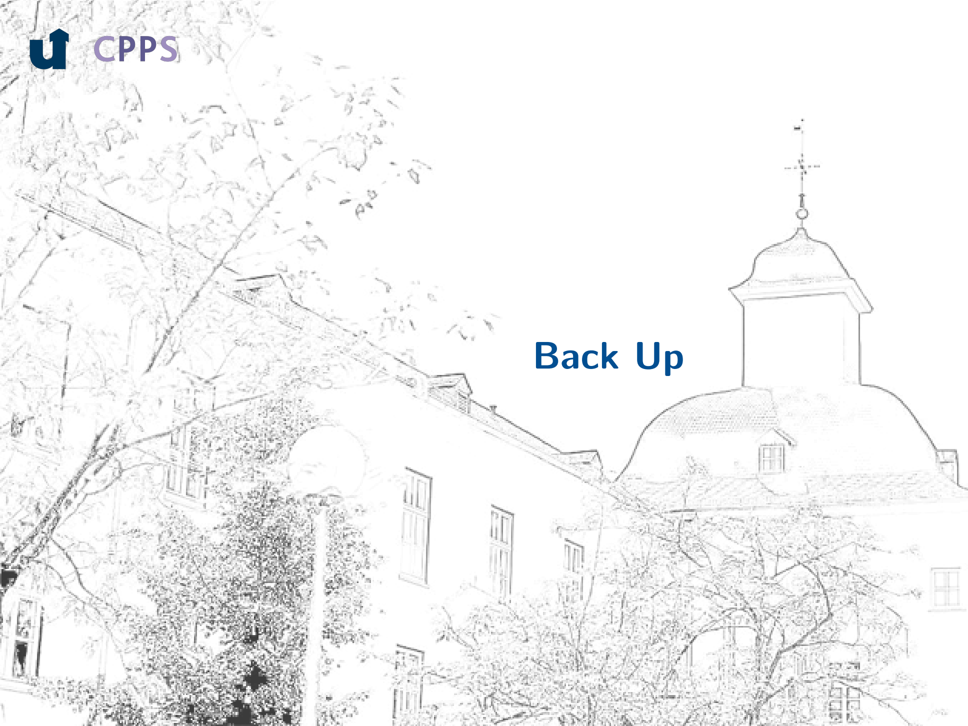
Normalisation of $bb4\ell$ cross section

How to normalise $bb4\ell$ MC sample?

- normalise the cross-section of all $bb4\ell$ events, which where projected onto a $t\bar{t}$ resonance history to the [NNLO QCD+NNLL on-shell $t\bar{t}$ cross section] and $bb4\ell$ events projected onto a tW resonance history to [NLO+NNLL cross section tW cross section]
- scale to $t\bar{t} + tW$ sum of higher order cross-sections
- total cross section needs to be scaled to data in the fit by analyses (not possible for all)

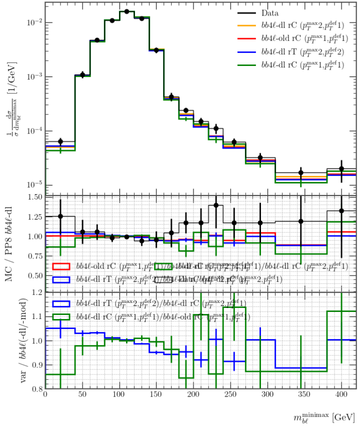
NNLO reweighting of $bb4\ell$ events with $t\bar{t}$ resonance history

Should we reweight $bb4\ell$ events projected onto $t\bar{t}$ resonance history to on-shell $t\bar{t}$ higher-order predictions?
$\rightarrow$ more in Diptaparnas talk



Back Up

Different $bb4\ell$ version and matching settings



$\rightarrow$ reasonable agreement in reco-distr. (also reported by CMS)

What is different between new and old $bb4\ell$ sample?

- $bb4\ell$ version
  - corrected matching factor between 4FNS ME and 5FNS PDF
  - inverse width corrections can be used in new $bb4\ell$ (effect small)
  - resonance histories: old $bb4\ell$: $t\bar{t}$ and $Z \rightarrow WW$, new $bb4\ell$: $t\bar{t}$, $tW^-\bar{b}$, $\bar{t}W^+b$
- matching settings:
  old ATLAS $bb4\ell$ sample: $p_T^{\rm maxMatch} = 0/1$, $p_T^{\rm def} = 1$
  new ATLAS $bb4\ell$ sample: $p_T^{\rm maxMatch} = 2$, $p_T^{\rm def} = 2$
- recoil settings:
  old ATLAS $bb4\ell$ sample: recoil-to-colour
  new ATLAS $bb4\ell$ sample: recoil-to-top

Cross sections

NLO+PS cross sections (dilepton):

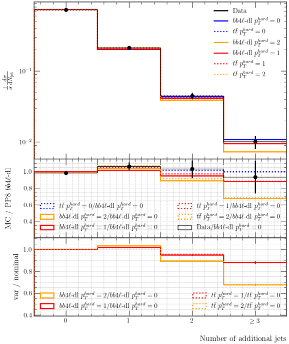
- $bb4\ell$: 87.1 pb
- $bb4\ell$ (inv. width corr.): 81.9 pb
- $t\bar{t}$ hvq: 76.9 pb
- tW DR: 7.6 pb
- tW DS: 7.5 pb
- $t\bar{t}+tW$ DR: 84.5 pb

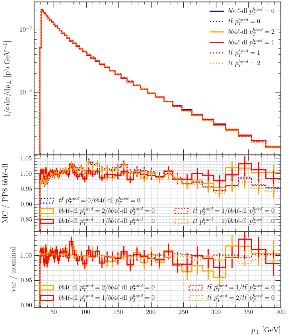
Higher-order cross-sections (inclusive $t\bar{t}$, $t\bar{t}$ dilepton branching ratio 10.5 %):

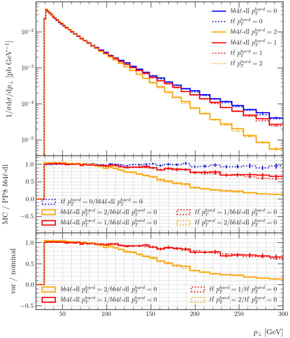
- 833.9 pb [Comput.Phys.Commun. 185 (2014) 2930] [Recommendations]
- 79.3 pb [hep-ph/2102.11300] [Recommendations]

$bb4\ell$ systematics: pThard variation

NLO+PS matching uncertainty introduced for ATLAS top-quark MC samples in [ATL-PHYS-PUB-2023-029]
→ changing of the veto-scale of the Pythia8 parton shower via `pThard` variation
→ creating holes and overlaps in the phase space covered by Powheg and by Pythia8



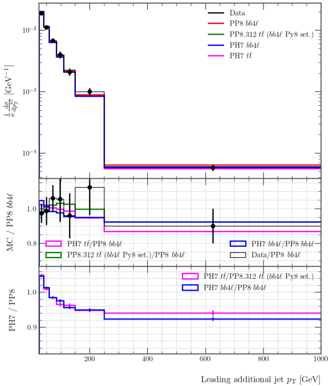


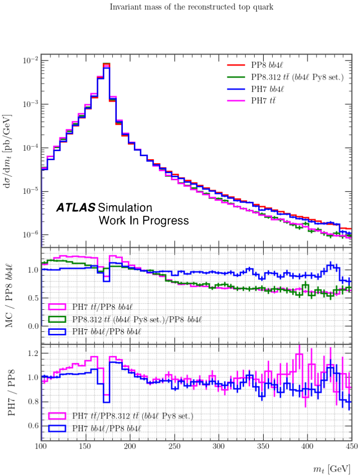


→ now technically also working in $bb4\ell$ (with modified $bb4\ell$ UserHook)

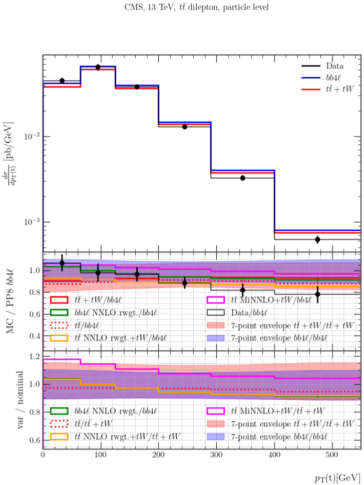
$bb4\ell$ systematics: Herwig7

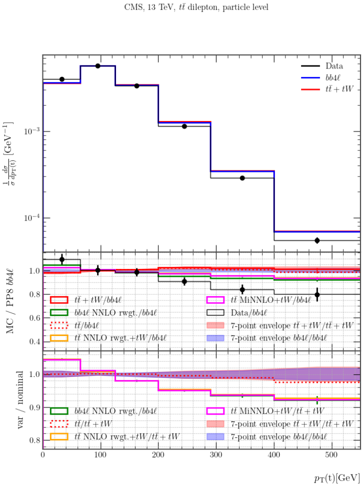
→ reasonable agreement between size of parton shower uncertainty in $bb4\ell$ (with dedicated matching) and $t\bar{t}$



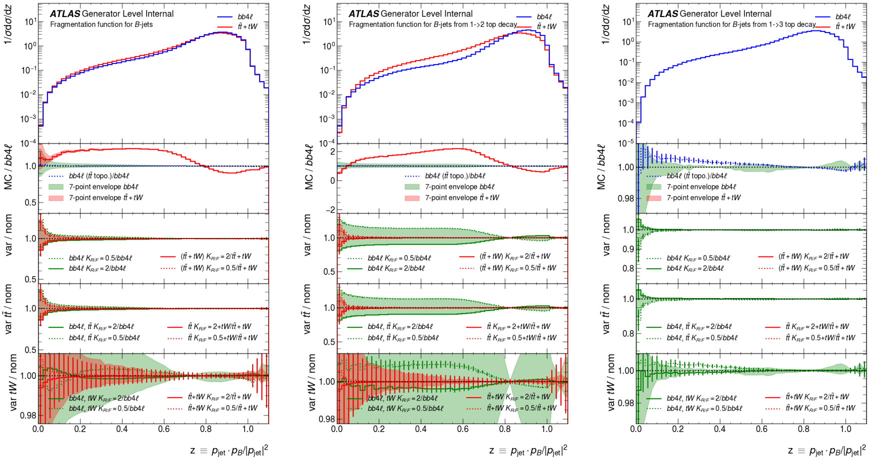


Partonic top reweighting

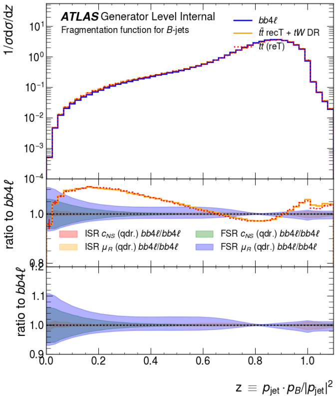




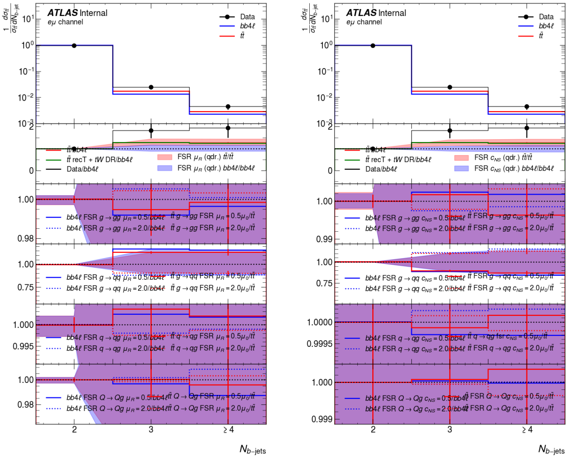
ME scale variation in b-jet fragmentation function



Py8 splitting kernel variations in b-jet fragmentation function



Number of b-jets: splitting kernel variation



$bb4\ell$ nominal MC sample

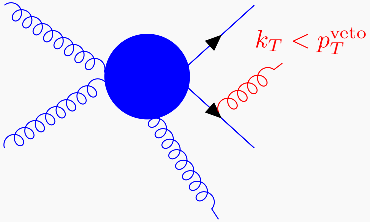
$p_{\mathrm{T}}^{\mathrm{def}}$ setting

Powheg+Pythia8 matching:

Py8 unrestricted shower + veto Py8 emissions if $k_T > p_T^{\mathrm{veto}}$

Matching settings:

- **veto scale $p_{\mathrm{T}}^{\mathrm{veto}}$**
  `pThard=0`: p_T of Powheg emission w.r.t. its emitter with Powheg p_T defintion
- **k_{T} definition for PS emissions**
  `pTdef=2`: use Pythia8 p_{T} defintion
  `pTdef=1`: use Powheg p_{T} defintion



$bb4\ell$ nominal MC sample

$p_{\mathrm{T}}^{\mathrm{def}}$ setting

Powheg+Pythia8 matching:

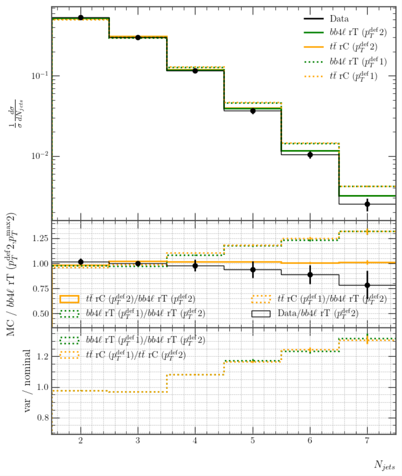
Py8 unrestricted shower + veto Py8 emissions if $k_T > p_T^{\mathrm{veto}}$

Matching settings:

- **veto scale $p_{\mathrm{T}}^{\mathrm{veto}}$**
  `pThard=0`: p_T of Powheg emission w.r.t. its emitter with Powheg p_T defintion
- **k_{T} definition for PS emissions**
  `pTdef=2`: use Pythia8 p_{T} defintion
  `pTdef=1`: use Powheg p_{T} defintion

$\rightarrow$ even though `pTdef=1` is theoretically more sensible, `pTdef=2` results in much better data-MC agreement in N_{jets} distribution

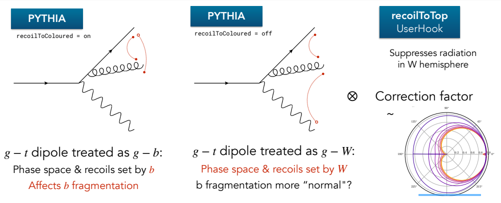
+ same setting as applied in ATLAS $t\bar{t}$ `hvq` and $t\bar{t}$ MiNNLO Powheg+Pythia8 MC sample



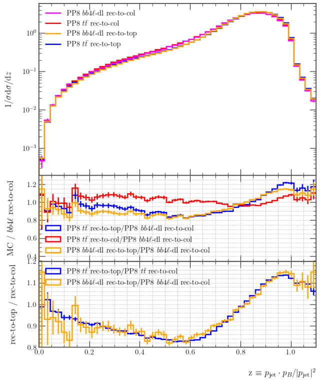
$bb4\ell$ nominal MC sample

Pythia8 recoil-to-top setting

→ **new nominal $bb4\ell$-dl sample has Py8 recoil-to-top setting as default!**



[Graphic from Peter Skands]

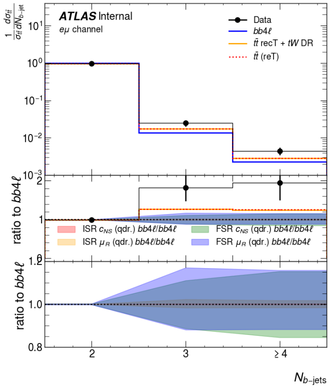


Recoil-to-top works for $bb4\ell$ events in [Py8 $\geq$ 8.313]

→ good agreement between uncertainty in $bb4\ell$ and $t\bar{t}$ (only affects 2nd and later gluon emission)

Recoil uncertainty definition: comparison to recoil-to-colour setting

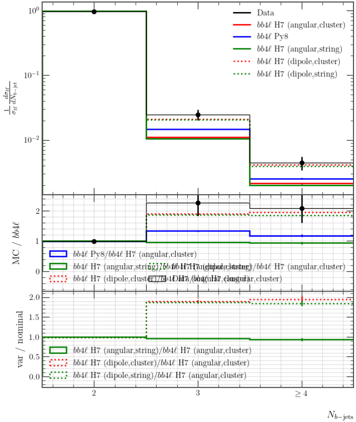
Number of b-jets



[arXiv:1811.12113] $t\bar{t}$ dilep, $N_b \geq 2$, $p_T^b > 25\,\text{GeV}$, $|\eta_b| < 2.5$

$\rightarrow$ number of additional b-jets not well described by neither $t\bar{t}$ `hvq` nor by $bb4\ell$

Number of b-jets: Herwig7 shower variations



Applying Herwig7 shower variations to $bb4\ell$:

- angular shower + cluster had. (solid)
- angular shower + string had. (solid)
- dipole shower + cluster had. (dashed)
- dipole shower + string had. (dashed)

[arXiv:1811.12113] $t\bar{t}$ dilep, $N_b \geq 2$, $p_T^b > 25$ GeV, $|\eta_b| < 2.5$

- large difference when changing the shower ordering in $bb4\ell$+H7 predictions (Py8 shower is also a dipole shower)
- $bb4\ell$+H7 dipole predictions show much better agreement in $N_b \geq 3$