Universität Siegen

CPPS Center for Particle Physics Siegen

Katharina Voß

Modelling systematics in ATLAS: Top quark pairs

CPPS Retreat, Meinerzhagen

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Modelling studies in ATLAS

Goal of modelling studies in ATLAS is the improvement in modelling uncertainties through:

- **Validation of improved nominal samples**
  (e.g. scale uncertainty reduction through higher order accuracy in event generation)
- **Improving modelling uncertainty prescription**
  (e.g. remove overestimation of modelling uncertainty through double-counting)

In the following slides:

An overview of the Powheg+Pythia8 [$t\bar{t}$ hvq] modelling uncertainty prescription and on-going studies within ATLAS to improve it

Uncertainty prescription for the $t\bar{t}$ process

Hard process generation

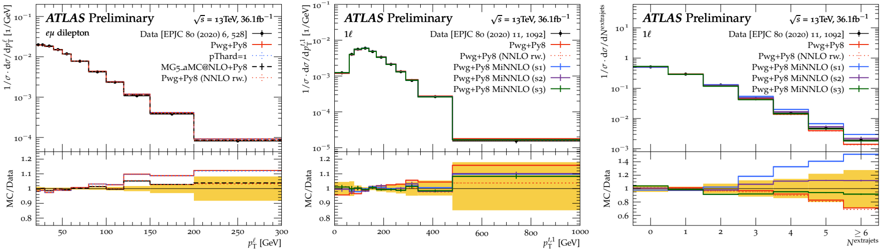
- **renormalisation and factorisation scale uncertainty**
  varying $(K_R, K_F) \in \{(1, 0.5), (1, 2), (0.5, 1), (2, 1)\}$ with $\mu_{R/F} = K_{R/F}\mu_0$
- **PDF uncertainty**
  PDF4LHC variations added in quadrature (nominal NNPDF3.0)
- **NNLO reweighting**
  use NNLO reweighting based on truth $p_{\mathrm{T}}^{t\bar{t}}$, $m_{t\bar{t}}$, p_{T}^{t} and $p_{\mathrm{T}}^{\bar{t}}$
- **h_{damp} variation**
  compare nominal $h_{\mathrm{damp}} = 1.5m_{\mathrm{top}}$ to $h_{\mathrm{damp}} = 3m_{\mathrm{top}}$
- **top quark mass**
  compare nominal $m_{\mathrm{top}} = 172.5$ GeV to $m_{\mathrm{top}} \in \{172.0, 173.0\}$ GeV samples

NNLO reweighting uncertainty

Improving modelling uncertainty prescription: NNLO reweighting
Validation of improved nominal model: $t\bar{t}$ MiNNLO

Top p_T modelled better by aMC@NLO compared to Powheg
$\rightarrow$ now introduced NNLO reweighting uncertainty (recursively, $p_T^{t\bar{t}}, m_{t\bar{t}}, p_T^t, p_T^{\bar{t}}$)
Moving to $t\bar{t}$ MiNNLO: studying matching options [ATL-PHYS-PUB-2023-029]

- (s1) $p_\mathrm{T}^\mathrm{def} = 1$ (Py8 default), $p_\mathrm{T}^\mathrm{hard} = 0$ (Py8 default)
- (s2) $p_\mathrm{T}^\mathrm{def} = 2$ (ATLAS $t\bar{t}$ default), $p_\mathrm{T}^\mathrm{hard} = 0$ (Py8 default)
- (s3) $p_\mathrm{T}^\mathrm{def} = 1$ (Py8 default), $p_\mathrm{T}^\mathrm{hard} = 1$



$t\bar{t}/tW$ interference

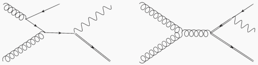
Validation of improved nominal sample: $bb4\ell$

Powheg+Pythia8 $t\bar{t}$ hvq (+tW DR)

Separate simulation of $t\bar{t}$ and [tW (Powheg+Pythia8)] final state at NLO+PS
→ afterwards stack simulated events

Why is this a problem?
Real emission correction to tW Born process includes $gg/q\bar{q} \to W^- t\bar{b}$:

$$\begin{aligned} |\mathcal{M}|^2 &= |\mathcal{M}^{Wt\bar{b}} + \mathcal{M}^{t(\bar{t}\to W\bar{b})}|^2 \\ &= |\mathcal{M}^{Wt\bar{b}}|^2 + 2\mathrm{Re}\mathcal{M}^{Wt\bar{b}}\mathcal{M}^{t(\bar{t}\to W\bar{b})} + |\mathcal{M}^{t(\bar{t}\to W\bar{b})}|^2 \end{aligned}$$



→ huge NLO corrections since $\sigma_{\mathrm{LO}}(Wt) < \sigma_{\mathrm{LO}}(t\bar{t})$

Does it makes sense to talk about a Wt production or only about WWb and $WWbb$?
Yes, in phase space regions with small interference (see e.g. [arXiv:0908.0631]):

- $|\mathcal{M}^{Wt\bar{b}}|^2$ NLO correction to Wt
- LO $t\bar{t}$ separate process that can be removed

$t\bar{t}/tW$ interference

Validation of improved nominal sample: *$bb4\ell$*

Powheg+Pythia8 $t\bar{t}$ hvq (+tW DR)

Real emission correction to tW Born process includes $gg/q\bar{q} \rightarrow W^{-}t\bar{b}$:

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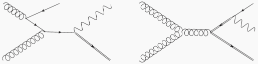


How can we check that applied cuts indeed reduce the sensitivity to the interference terms?
$\rightarrow$ compare two different approximations to remove $t\bar{t}$ effects in Wt NLO calculation

- Diagram Removal (DR): $\mathcal{M}^{\mathrm{DR}} = \mathcal{M}^{Wt\bar{b}} \rightarrow |\mathcal{M}^{DR}|^2 = |\mathcal{M}^{Wt\bar{b}}|^2$
- Diagram Subtraction (DS): $|\mathcal{M}^{\mathrm{DS}}|^2 = |\mathcal{M}^{Wt\bar{b}} + \mathcal{M}^{t(\bar{t}\rightarrow W\bar{b})}|^2 - \mathcal{C}^{\mathrm{SUB}}$, with $\mathcal{C}^{\mathrm{SUB}} \rightarrow |\mathcal{M}^{t(\bar{t}\rightarrow W\bar{b})}|^2$ for $m_{Wb} \rightarrow m_t$

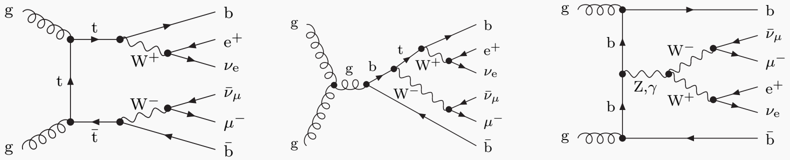
$|\mathcal{M}^{\mathrm{DS}}|^2 - |\mathcal{M}^{\mathrm{DR}}|^2 =$ interference term $= 2\mathrm{Re}\mathcal{M}^{Wt\bar{b}}\mathcal{M}^{t(\bar{t}\rightarrow W\bar{b})}$ (if $\mathcal{C}^{\mathrm{SUB}} - |\mathcal{M}^{t(\bar{t}\rightarrow W\bar{b})}|^2$ small)
$\rightarrow$ if $|\mathcal{M}^{\mathrm{DS}}|^2 \sim |\mathcal{M}^{\mathrm{DR}}|^2$ (DR/DS uncertainty small), then in phase space region with small interference between $t\bar{t}$ and tW

$t\bar{t}/tW$ interference

Validation of improved nominal sample: *bb4ℓ*

bb4ℓ [arXiv:1607.04538] [arXiv:2307.15653]

Matrix element calculation includes double-, single- and non-resonant diagrams
→ interference terms fully included without approximation at NLO
→ no additional *tW* sample to describe *WWbb* final state



Currently developing modelling uncertainty prescription for the *bb4ℓ* process

Strategy: Compare systematic uncertainties in Powheg+Pythia8 $t\bar{t}$ and *bb4ℓ* using the same prescription

Uncertainty prescription for the $t\bar{t}$ process

Improving modelling uncertainty prescription: targeted matching uncertainty

Matching uncertainty [ATL-PHYS-PUB-2023-029]

- **Pythia 8 $p_{\mathrm{T}}^{\mathrm{hard}}$ variation**
  compare nominal $p_{\mathrm{T}}^{\mathrm{hard}} = 0$ to $p_{\mathrm{T}}^{\mathrm{hard}} = 1$ sample

Previous matching uncertainty definition in ATLAS: Pwg+Py8 vs. MG_aMC@NLO+Py8
→ convolutes multiple modelling differences, not only matching uncertainty!
→ updated matching uncertainty: variation of Py8 parameter $p_{\mathrm{T}}^{\mathrm{hard}}$ [SciPostPhys.12(2022)010]

What is $p_{\mathrm{T}}^{\mathrm{hard}}$?

Showering of Pwg LHE files with Py8: vetoed shower = generate emissions with Py8 in full, unrestricted phase space, but then veto emissions which have hardness scale > Pwg scale
How is the Pwg scale determined?

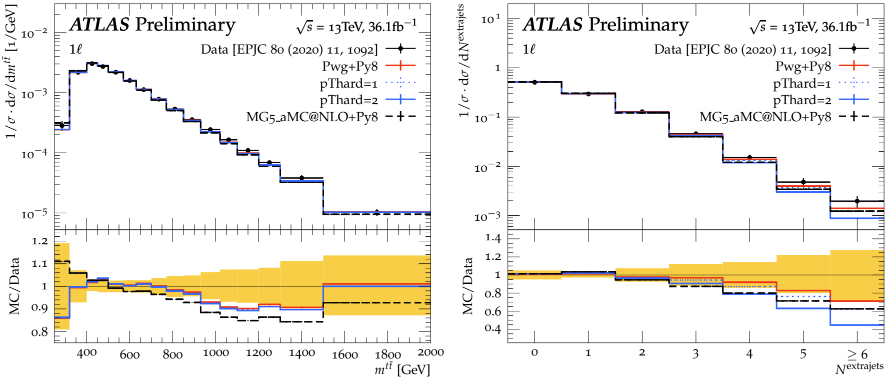
- Born-like events: SCALUP value of LHE information
- real emission events:
  - $p_{\mathrm{T}}^{\mathrm{hard}} = 0$ (default): SCALUP value of LHE information
  - $p_{\mathrm{T}}^{\mathrm{hard}} = 1$: min(p_{T} of Pwg emission w.r.t. all other FS particles or beam axis)
  - $p_{\mathrm{T}}^{\mathrm{hard}} = 2$: min(p_{T} of all FS particles w.r.t. each-other and w.r.t. the beam axis)

Uncertainty prescription for the $t\bar{t}$ process

Improving modelling uncertainty prescription: targeted matching uncertainty

Matching uncertainty [ATL-PHYS-PUB-2023-029]

- **Pythia 8 p_T^{hard} variation**
  compare nominal $p_T^{hard} = 0$ to $p_T^{hard} = 1$ sample



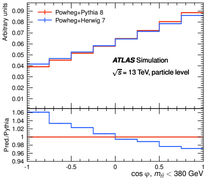
Uncertainty prescription for the $t\bar{t}$ process

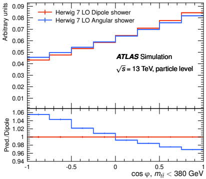
Parton shower uncertainties

- **initial state radiation**
  Pythia 8 Var3c variations, vary ISR $\alpha_S(M_Z) = \{0.115, 0.140\}$, nominal $\alpha_S(M_Z) = 0.127$ [ATL-PHYS-PUB-2014-021]
- **final state radiation**
  vary μ_R FSR splitting kernels by factor 0.5 and 2
- **parton shower**
  comparison of nominal Pwg+Py8 with Pwg+Herwig 7 (H7)

Improving modelling uncertainty prescription: factorised parton shower uncertainty

Example entanglement in $t\bar{t}$ [2311.07288]:





$\rightarrow$ dipole vs angular ordered shower has the largest influence on the Py8 vs H7 difference in the entanglement measurement

Goal: factorised parton shower uncertainty to understand which part of the parton shower modelling (e.g. shower ordering or hadronisation) influences measurement the most

Uncertainty prescription for the $t\bar{t}$ process

Specialised uncertainty definitions

- **top line shape** (only for analysis in off-shell region)
  comparison of nominal Pwg+Py8 to Pwg+MadSpin+Py8 $t\bar{t}$ sample
- **recoil-to-top**
  compare nominal (recoil-to-colour) to alternative recoil-to-top sample
- **underlying event**
  Py8 A14 Var1 variations (MPI and UE tuning parameters) [ATL-PHYS-PUB-2014-021]
- **colour reconnection**
  comparison of nominal to tuned results with different CR models CR1 and CR2 [ATL-PHYS-PUB-2017-008]

Top lineshape uncertainty

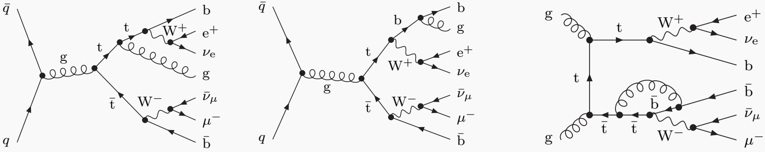
Improving modelling uncertainty prescription: dedicated line shape uncertainty
Validation of improved nominal sample: *bb4ℓ*

Pwhg+Py8 $t\bar{t}$ `hvq`: narrow width approximation + LO top decay

Narrow width approximation: simulate $t\bar{t}$ with on-shell final state particles and subsequent top decay at LO with Breit-Wigner smearing of the top quark invariant masses
[Frixione,Laenen,Motylinski,Webber-method arXiv:0702198]

bb4ℓ: complete offshell effects and top decay at NLO

Description of top decay at NLO:

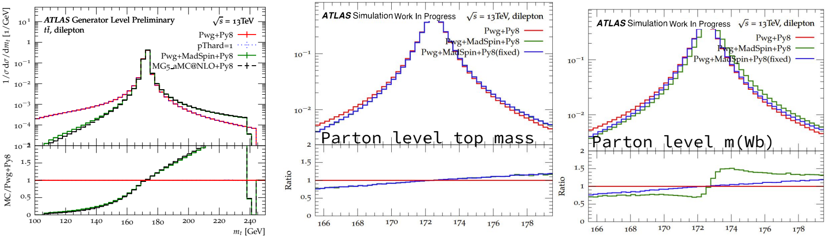


& top off-shell effects are included without approximation since full top quark propagator is used in NLO matrix element calculation

Top lineshape uncertainty

Improving modelling uncertainty prescription: dedicated line shape uncertainty
Validation of improved nominal sample: *bb*4ℓ

Recently introduced top line shape uncertainty in the Powheg+Pythia8 `hvq` $t\bar{t}$ uncertainty prescription to quantify the discrepancy between `hvq` internal and external MadSpin implementations of Breit-Wigner smearing of top quark mass [ATL-PHYS-PUB-2023-029]



→ top line shape uncertainty can be sizeable e.g. in top mass measurements → uncertainty removed when moving to *bb*4ℓ

Conclusions and Outlook

Goal of modelling studies in ATLAS is the improvement in modelling uncertainties through:

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  - $bb4\ell$
  - $t\bar{t}$ MiNNLO
  - $t\bar{t}$ Powheg+VINCIA
- **Improving modelling uncertainty prescription**
  - recently finished: p_T^{hard}, lineshape, NNLO reweighting
  - factorised parton shower uncertainty study

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Thank you for your attention!

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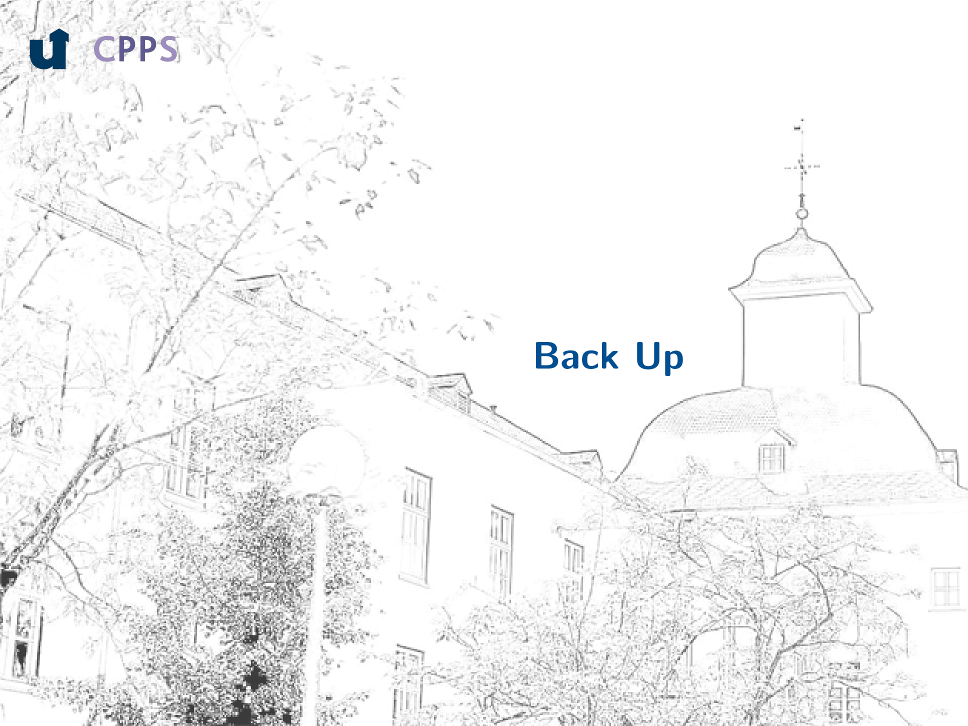


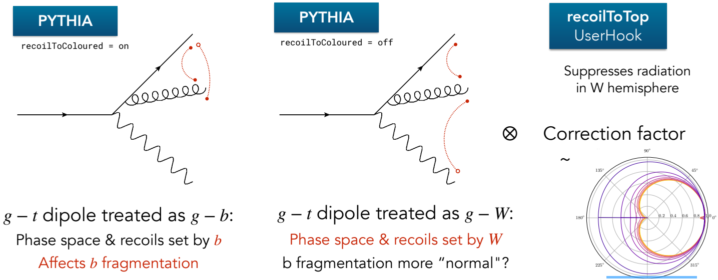
Back Up

Recoil uncertainty

Validation of improved nominal sample: Powheg+VINCIA

ATLAS default $t\bar{t}$ Pwg+Py8 setting: `recoilToColoured = on` $\rightarrow$ out of cone radiation is supressed

Recoil-to-top: W-boson as a recoiler (more out of cone radiation), but multiply with correction factor $\rightarrow$ in principle the better description!



(graphic taken from [Peter Skands])

Uncertainty prescription: $t\bar{t}$ Pwg+Py8 vs. $t\bar{t}$ Pwg+Py8 with [TopRecoil UserHook]

$\rightarrow$ especially top mass measurement found to be sensitive to this uncertainty

$\rightarrow$ $t\bar{t}$ Powheg+VINCIA sample would provide correct emission pattern, matching options currently studied in ATLAS

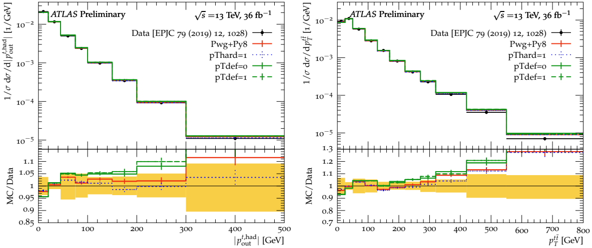
Comparison with p_T^{def} variation

What is p_T^{def}?

Which p_T definition is used when calculating the hardness in the matching?

- $p_T^{def} = 0$: Pwg ISR p_T definition for ISR and FSR
- $p_T^{def} = 1$ (Pythia 8 default): Pwg ISR p_T and FSR d_{ij} definition
- $p_T^{def} = 2$ (ATLAS default): Pythia 8 p_T definition

→ ATLAS default $p_T^{def} = 2$ chosen due to better data-MC agreement



→ p_T^{def} variation has large effect on presented variables, mostly worsening data-MC agreement