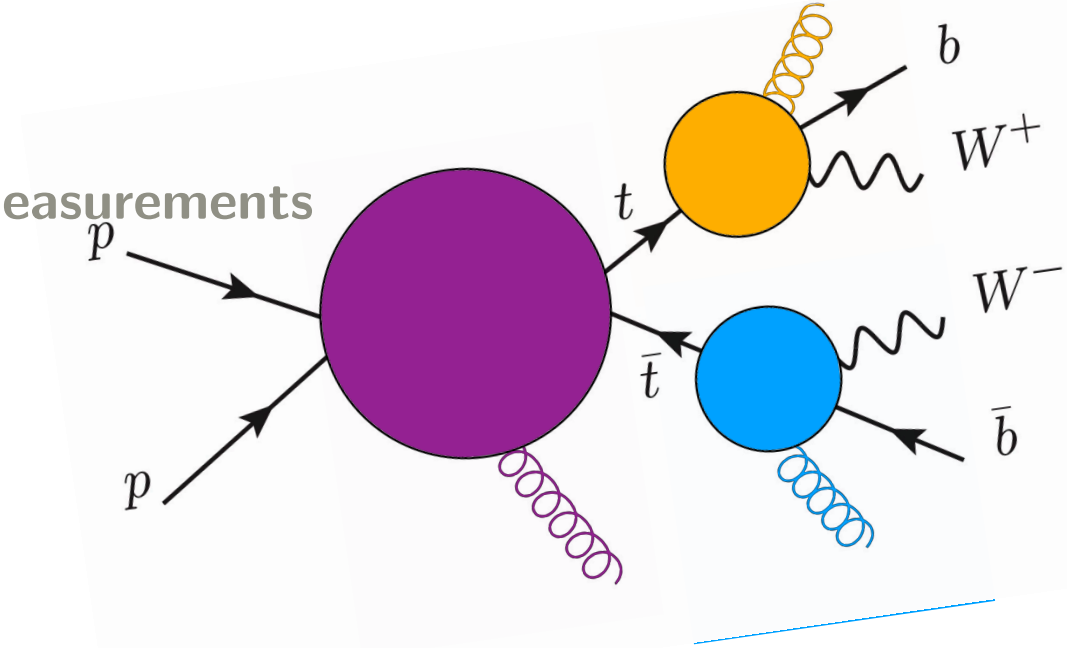
Katharina Voß on behalf of the ATLAS Collaboration

Modelling uncertainties of the ATLAS $bb4\ell$ Monte Carlo sample

Workshop on top-quark mass measurements

11th November 2025



$bb4\ell$ systematic uncertainty study in ATLAS

→ focussing on dilepton version of [$bb4\ell$], i.e. $b\bar{b}\ell^-\ell'^+\bar{\nu}_\ell\nu_{\ell'}$ final state

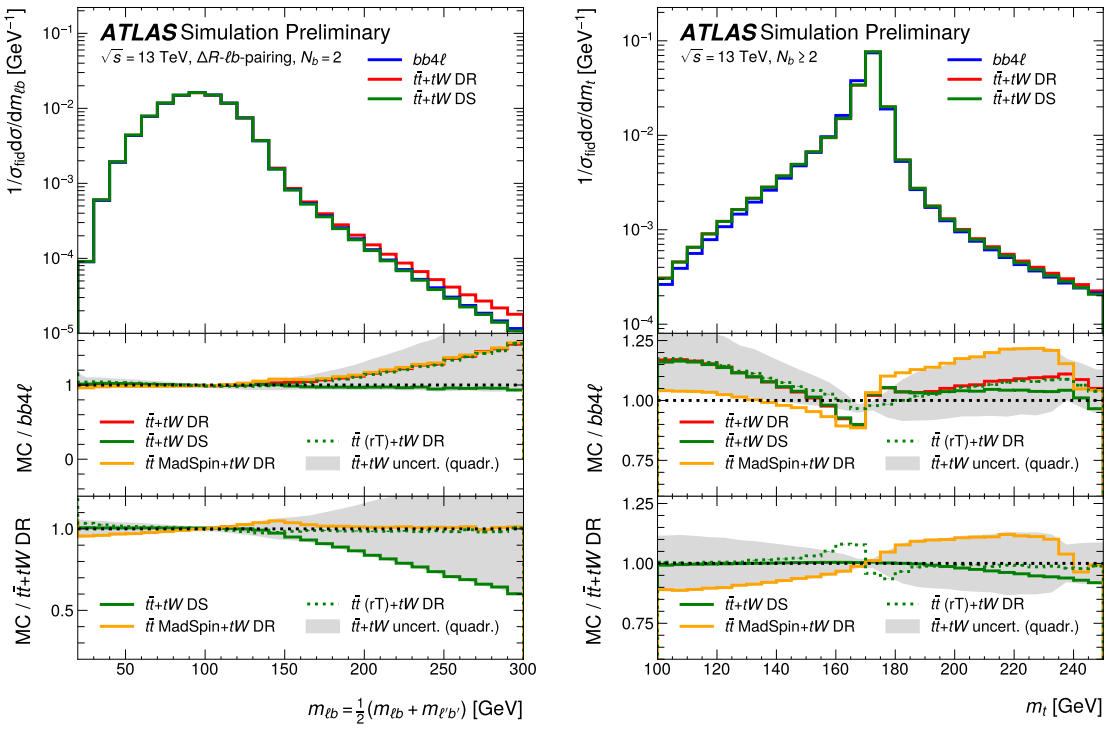
Aim of the $bb4\ell$ systematic uncertainty study

- comparison of $bb4\ell$ ATLAS nominal sample to $t\bar{t} + tW$ MC ATLAS sample
- development of systematic uncertainty model for $bb4\ell$
- comparison of size of systematic uncertainties in $bb4\ell$ and $t\bar{t}(+tW)$

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-quark decay description at NLO
  → good approximation in $t\bar{t}$ Powheg+Pythia8 through matrix element corrections in Pythia8 [JHEP 10 (2023) 008]



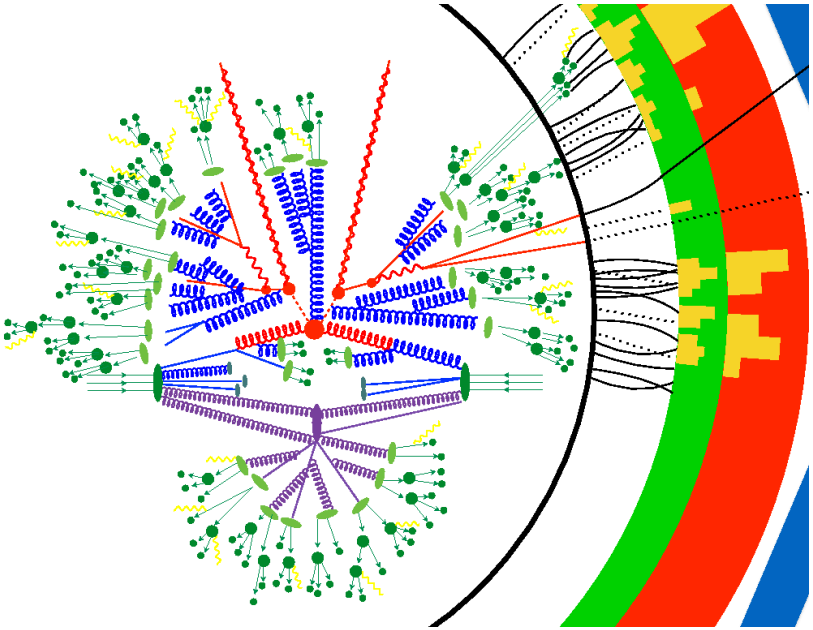
Overview of $bb4\ell$ modelling uncertainties

Uncertainties in

- **Powheg hard process**
  - μ_R, μ_F scale variation
  - PDF uncertainties
  - h_{damp}
  - $bb4\ell$: α_S in Powheg Sudakov
- **Powheg-Pythia8 matching**
  - $p_{\text{T}}^{\text{hard}}$ 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

General strategy

Compare size of modelling uncertainties in $bb4\ell$ and $t\bar{t}$
$\rightarrow$ understand differences



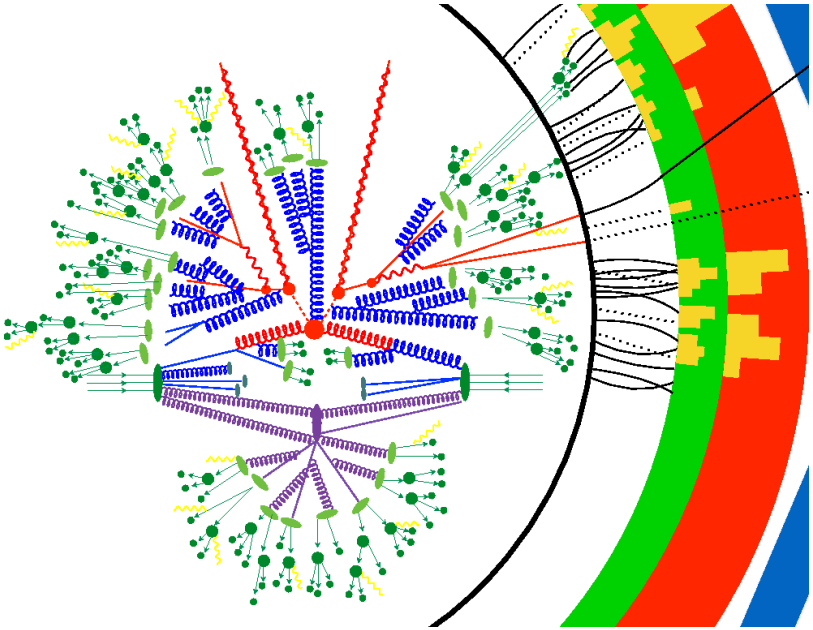
Overview of $bb4\ell$ modelling uncertainties

Uncertainties in

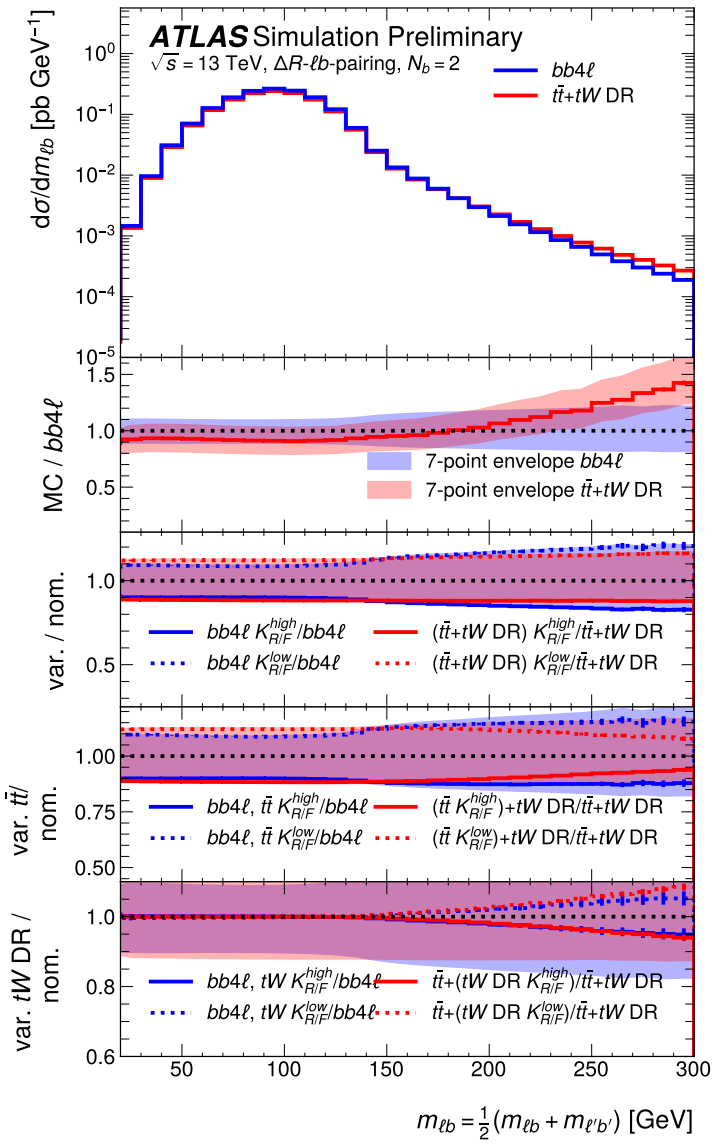
- **Powheg hard process**
  - μ_R, μ_F scale variation
  - PDF uncertainties
  - h_{damp}
  - $bb4\ell$: α_S in Powheg Sudakov
- **Powheg-Pythia8 matching**
  - $p_{\text{T}}^{\text{hard}}$ variation
  - $bb4\ell$: scale resonance veto
- **Pythia8 parton shower**
  - A14 Var1 tune variations (underlying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

General strategy

Compare size of modelling uncertainties in $bb4\ell$ and $t\bar{t}$
$\rightarrow$ understand differences



$bb4\ell$ systematics: ME scale variations



Generally good agreement between ME scale uncertainty in $bb4\ell$ and $t\bar{t} + tW$

$\rightarrow$ slightly larger $bb4\ell$ ME uncertainties in $m_{\ell b}$-tail and more shape effects

Also reasonable agreement when split into resonance histories
$\rightarrow$ even though central scale definitions differ:

$$t\bar{t} \text{ topo} \quad \begin{cases} \mu_0^{bb4\ell(t\bar{t})} = [(m_t^2 + p_{T,t}^2)(m_{\bar{t}}^2 + p_{T,\bar{t}}^2)]^{1/4} \\ \mu_0^{t\bar{t}} = \sqrt{m_{\text{top}}^2 + p_{T,t}^2} \end{cases}$$

$$tW \text{ topo} \quad \begin{cases} \mu_0^{bb4\ell(tW)} = [(m_t^2 + p_{T,t}^2)(m_{\bar{b}}^2 + p_{T,\bar{b}}^2)]^{1/4} \\ \mu_0^{tW} = \sqrt{m_{\text{top}}^2 + p_{T,t}^2} + \sqrt{m_{\text{W}}^2 + p_{T,W}^2}(+p_T^j) \end{cases}$$

Dedicated $bb4\ell$ parton shower matching

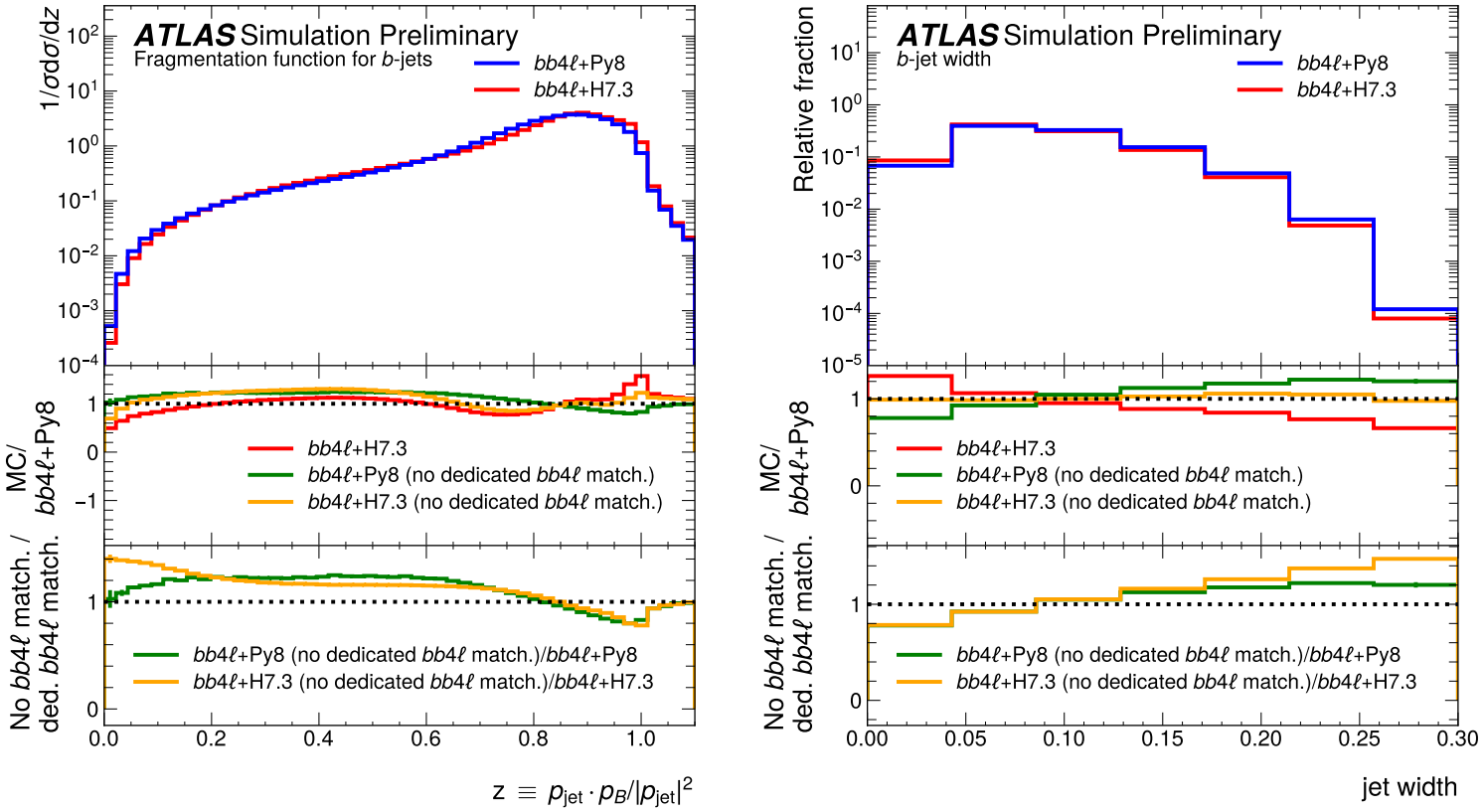
$t\bar{t} \rightarrow$ emission only from the production process

$bb4\ell \rightarrow$ merge emissions into single event with multiple emissions (`allrad` scheme)

$\rightarrow$ 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)]

Influence of dedicated $bb4\ell$-PS matching



No dedicated $bb4\ell$-PS matching:
→ in general higher shower starting scale of emissions from top-quark decay
→ more radiation off of b-quarks: less high-z B-hadrons and broader b-jets
Very good agreement of dedicated $bb4\ell$ matching effect in Py8 and H7 in b-jet properties

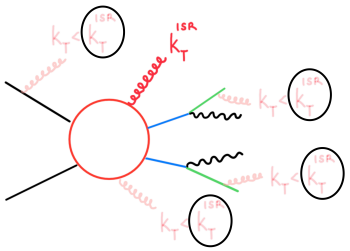
Matching uncertainty in production

Matching uncertainty definition in production
= varying matching scale $k_{\mathrm{T}}^{\mathrm{ISR}}$

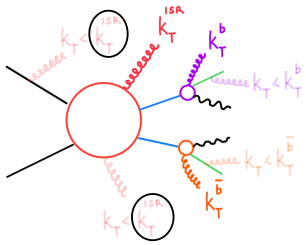
- $p_{\mathrm{T}}^{\mathrm{hard}} = 0$ (default): p_{T} of Powheg emission w.r.t. emitter (SCALUP)
- $p_{\mathrm{T}}^{\mathrm{hard}} = 1$ (uncert. def.): min p_{T} of Powheg emission w.r.t. all incoming and outgoing partons
- $p_{\mathrm{T}}^{\mathrm{hard}} = 2$: min p_{T} of all final-state partons w.r.t. all incoming and outgoing partons

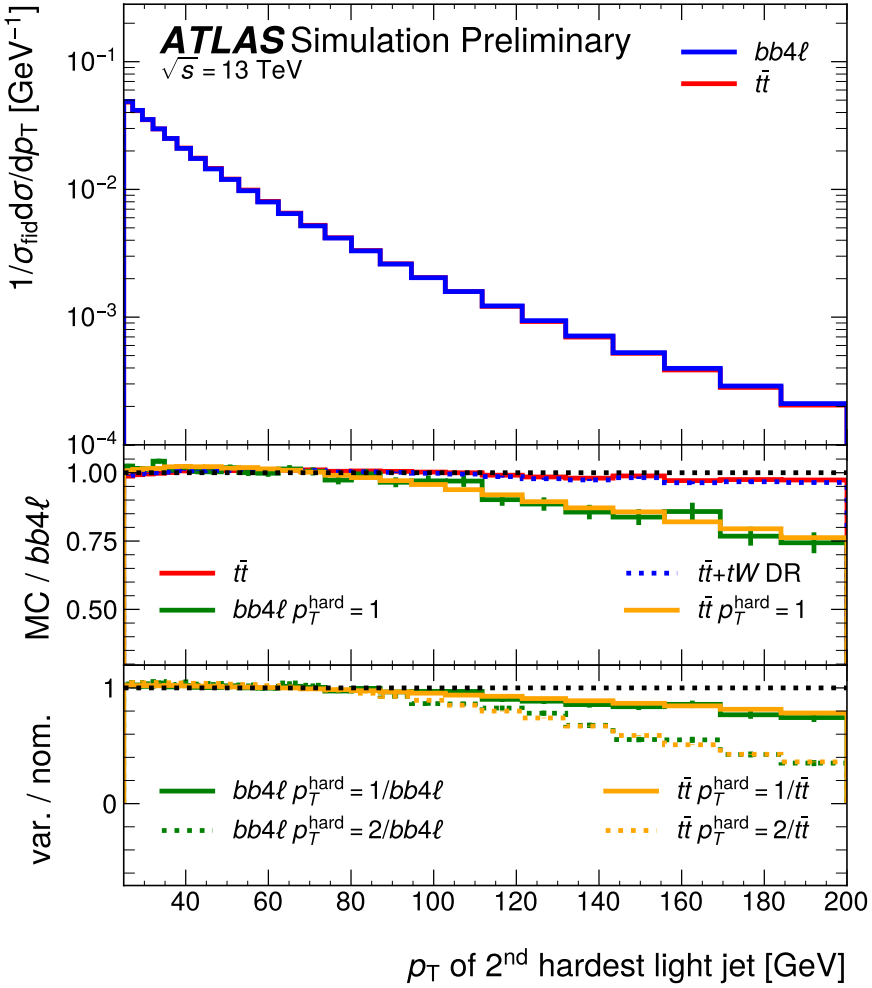
[ATL-PHYS-PUB-2023-029]

$t\bar{t}$+PS



$bb4\ell$+PS



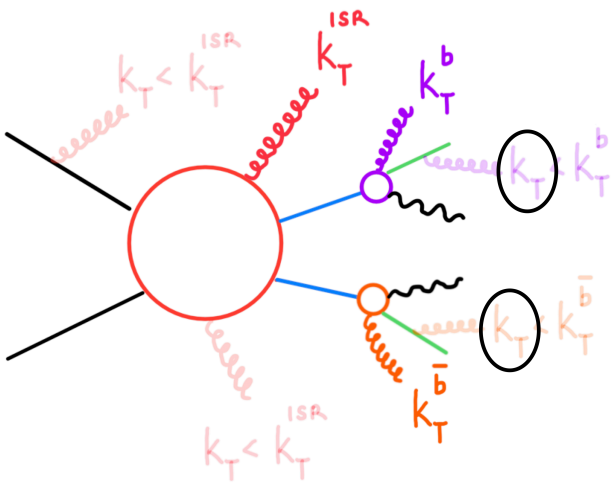


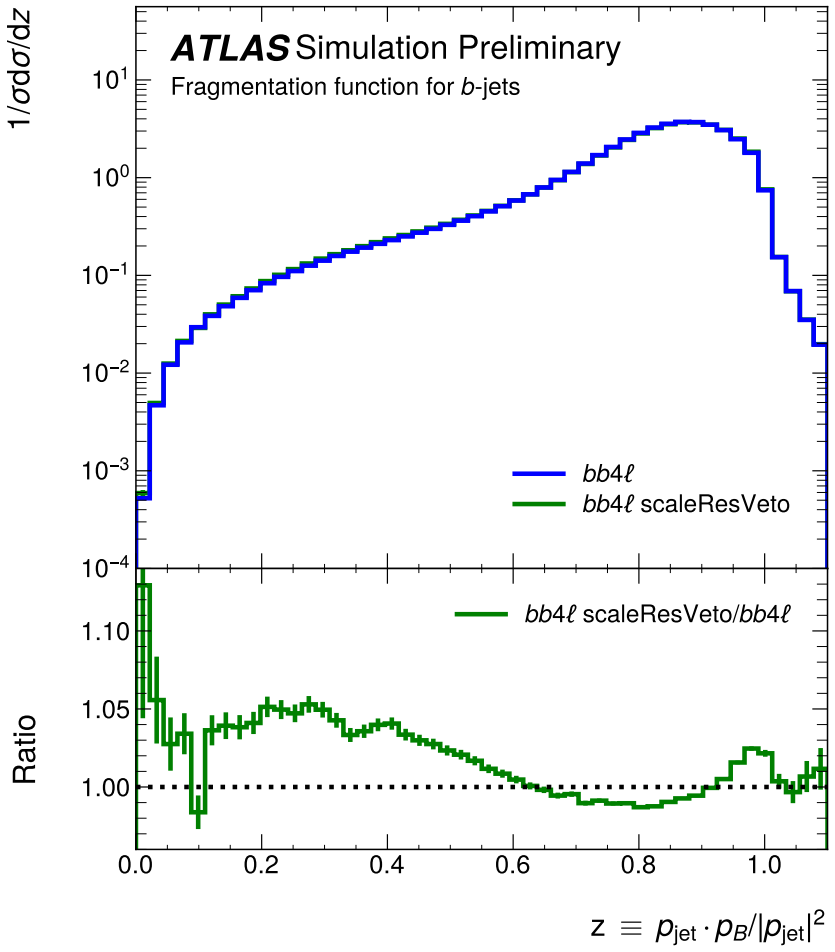
One sensitive variable: second leading light jet

Typically expected
→ from ISR parton shower emissions
→ same variation expected in $bb4\ell$ and $t\bar{t}$ ✓

Matching uncertainty in top-quark decay

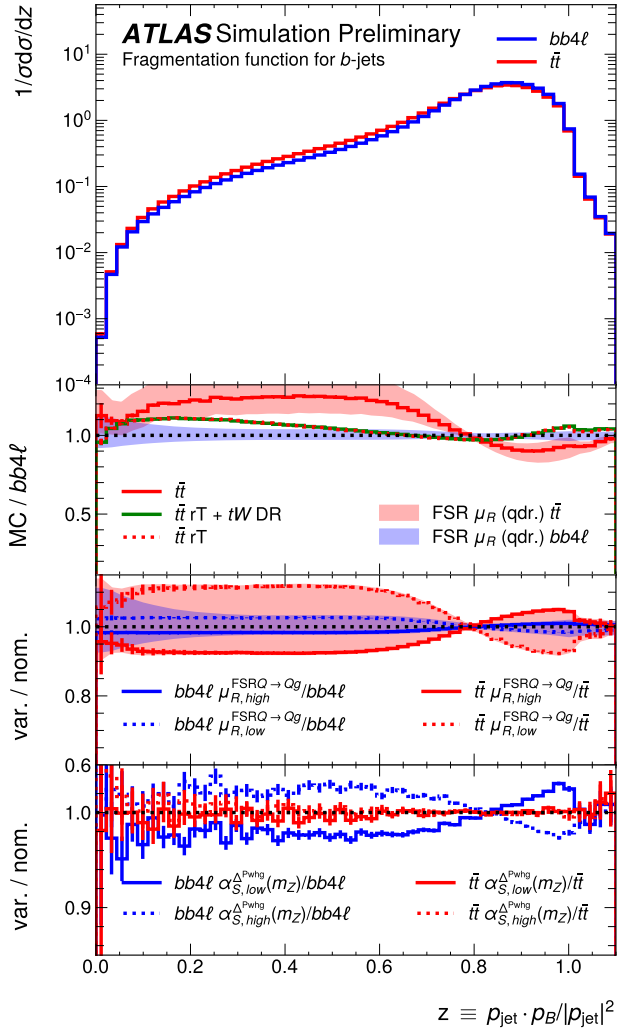
Matching uncertainty definition in top-quark decay
= vary k_T definition of PS emissions in top-quark decay
→ only applicable for $bb4\ell$ MC





Expectation: influence on b-jet properties ✓
(small influence on additional light jet distributions)

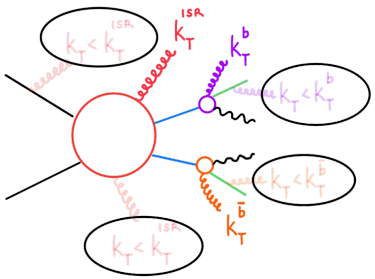
$bb4\ell$ systematics: FSR μ_R and α_S in Powheg Sudakov



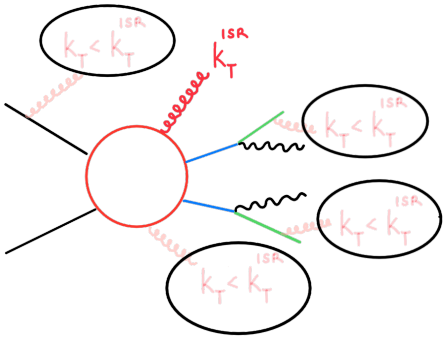
→ same influence of all μ_R splitting kernel variations except for FSR $Q \to Qg$ splitting kernel ($Q \in \{b, t\}$)

Possible explanation: NLO top decay description in $bb4\ell$

$bb4\ell =$

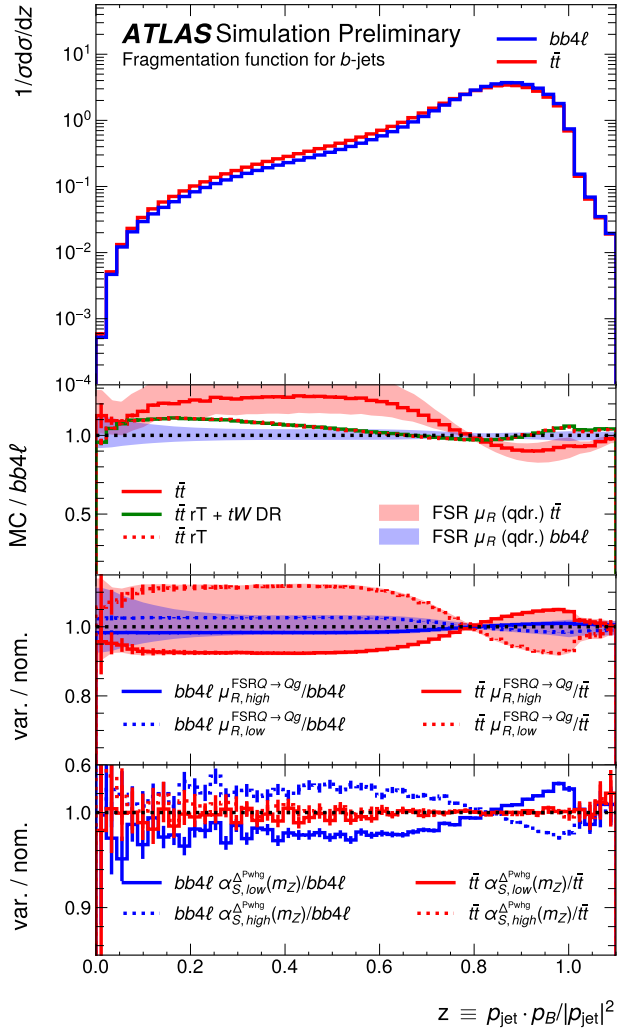


$t\bar{t} =$



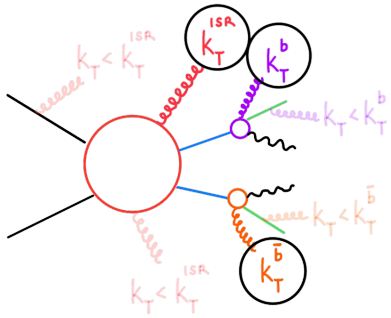
→ larger variation in $t\bar{t}$+PS ✓

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

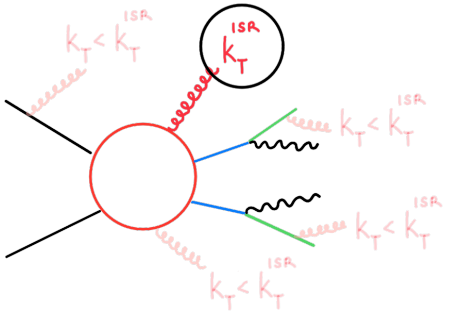


Vary α_S in Powheg Sudakov (by using PDF set with different $\alpha_S(M_Z)$ value) [Eur.Phys.J.C 78 (2018) 6, 458]

$bb4\ell =$



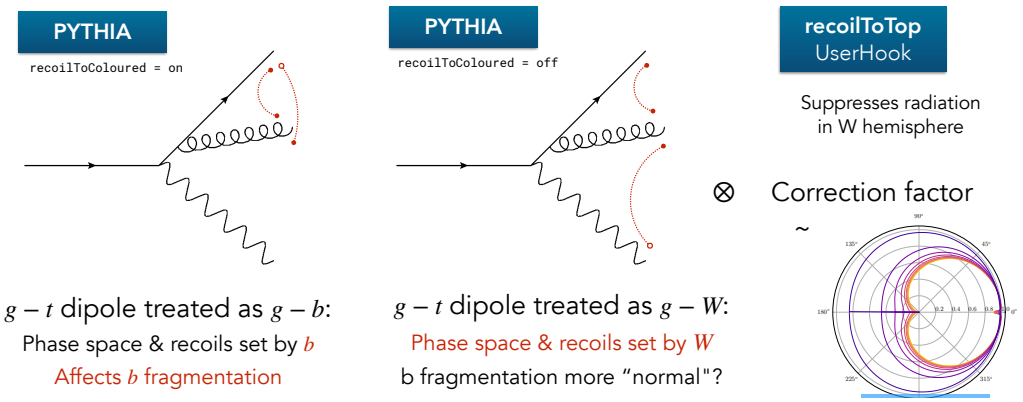
$t\bar{t} =$



$\rightarrow$ no variation in $t\bar{t}$+PS, but in $bb4\ell$+PS ✓

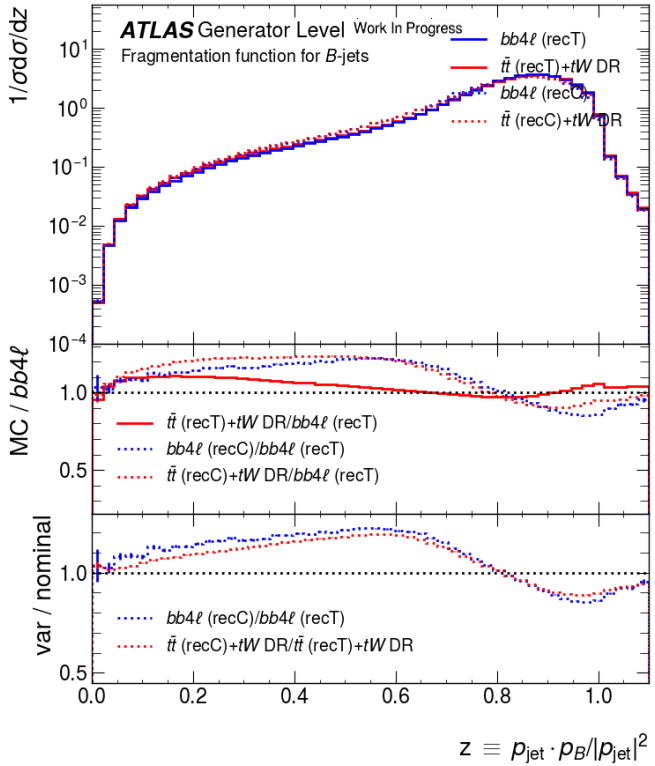
$bb4\ell$ systematics: recoil uncertainty

→ **new nominal $bb4\ell$-dl sample has Py8 recoil-to-top setting as default!**
Recoil uncertainty definition: comparison to recoil-to-colour setting



[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)

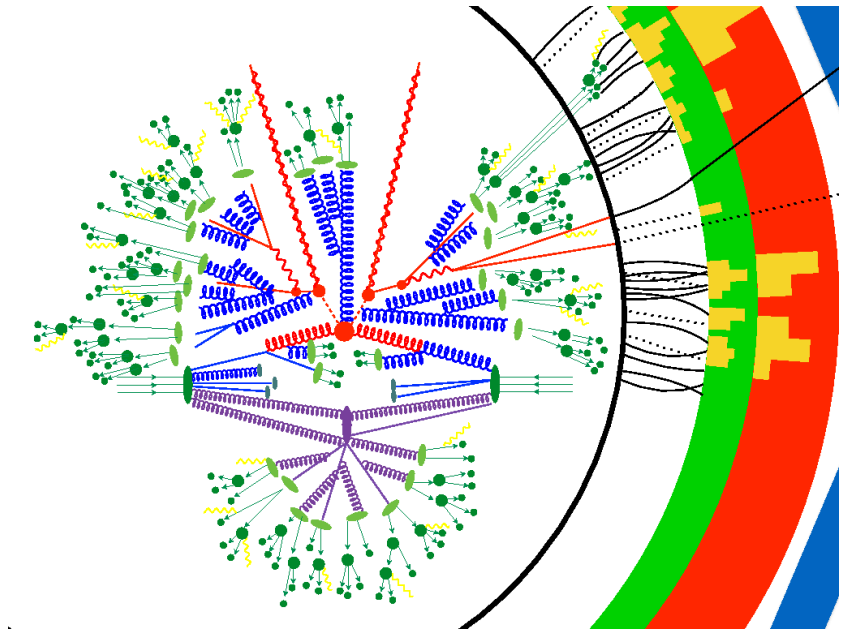
Conclusions

Uncertainties in

- **Powheg hard process**
  - μ_R, μ_F scale variation
  - PDF uncertainties
  - h_{damp}
  - $bb4\ell$: α_S in Powheg Sudakov
- **Powheg-Pythia8 matching**
  - $p_{\text{T}}^{\text{hard}}$ 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

Conclusions from this talk

- highlighted some aspects of $bb4\ell$ systematic uncertaintiy study in ATLAS
- studies described in [ATL-PHYS-PUB-2025-036]
- on-going work on systematic uncertainty study with Tomas Jezo, Jonas Lindert and Stefano Pozzorini



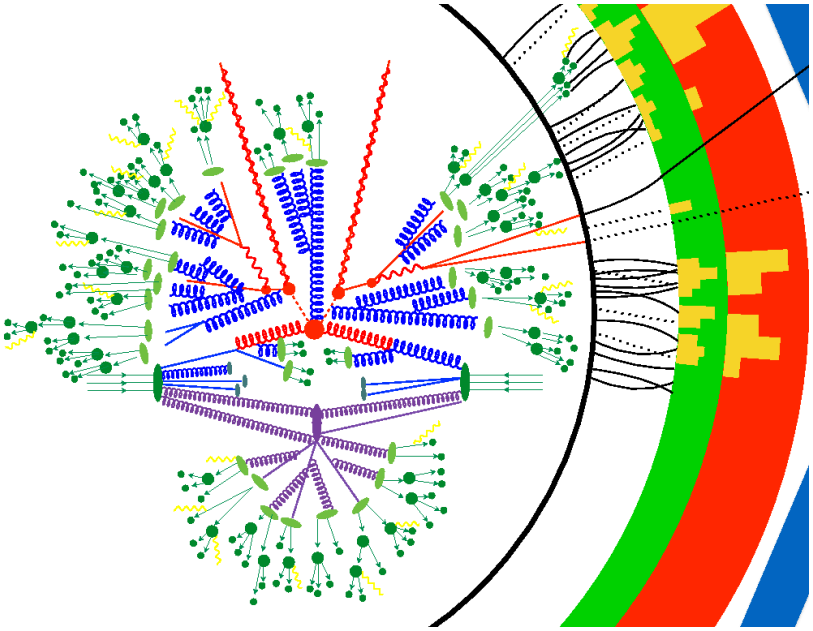
Conclusions

Uncertainties in

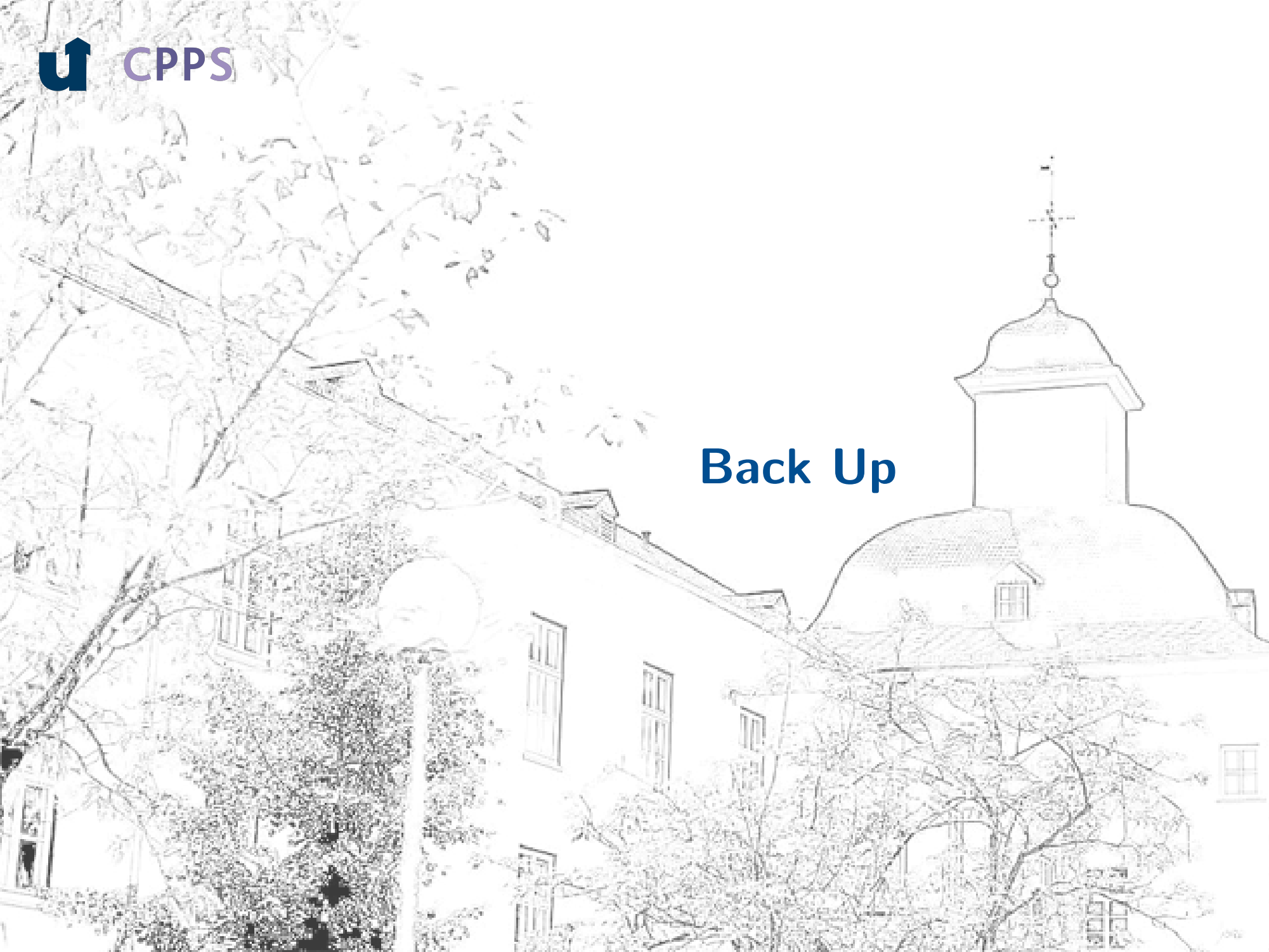
- **Powheg hard process**
  - μ_R, μ_F scale variation
  - PDF uncertainties
  - h_{damp}
  - $bb4\ell$: α_S in Powheg Sudakov
- **Powheg-Pythia8 matching**
  - p_T^{hard} variation
  - $bb4\ell$: scale resonance veto
- **Pythia8 parton shower**
  - A14 Var1 tune variations (underlying event variation)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

Conclusions from this talk

- highlighted some aspects of $bb4\ell$ systematic uncertaintiy study in ATLAS
- studies described in [ATL-PHYS-PUB-2025-036]
- on-going work on systematic uncertainty study with Tomas Jezo, Jonas Lindert and Stefano Pozzorini



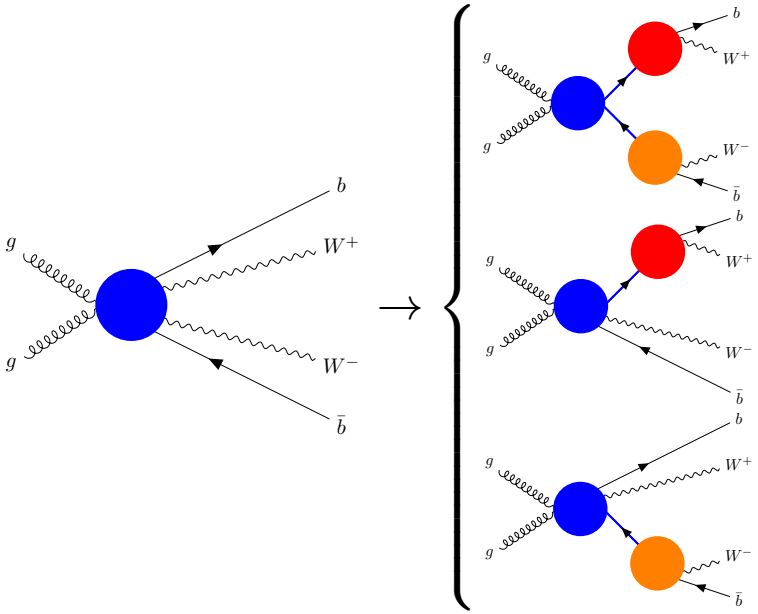
Thank you for your attention!

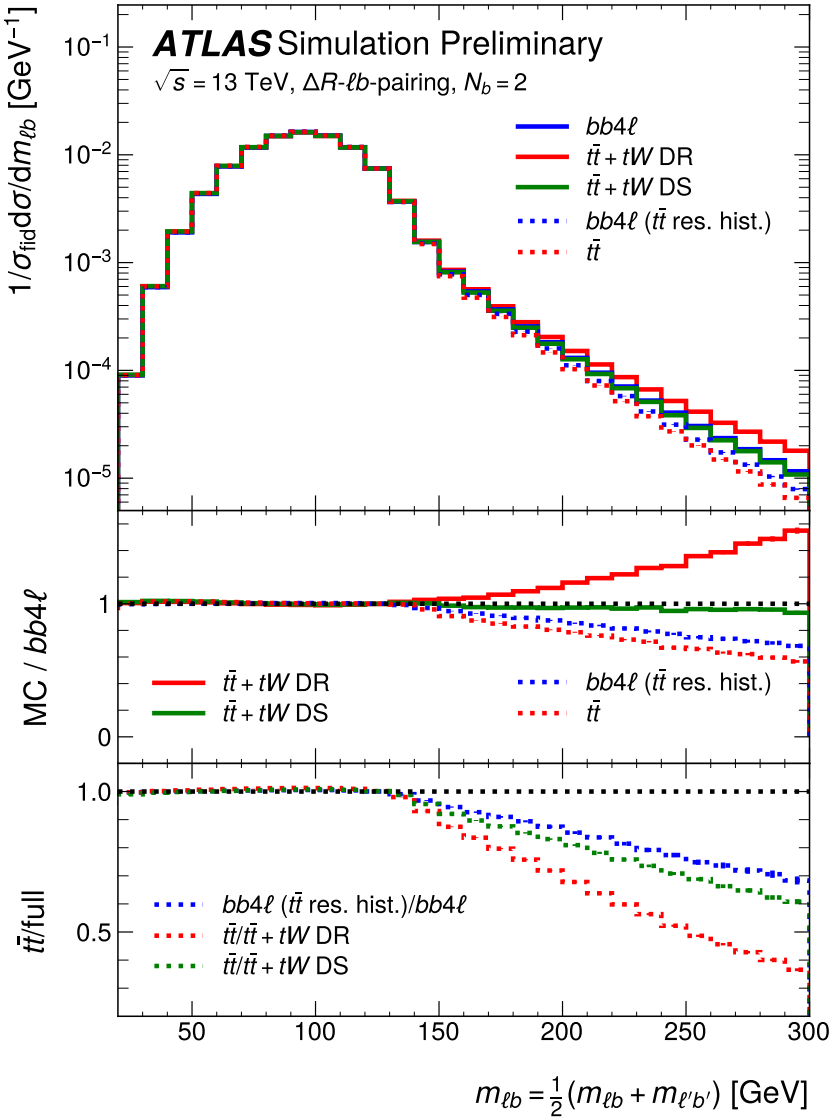


Back Up

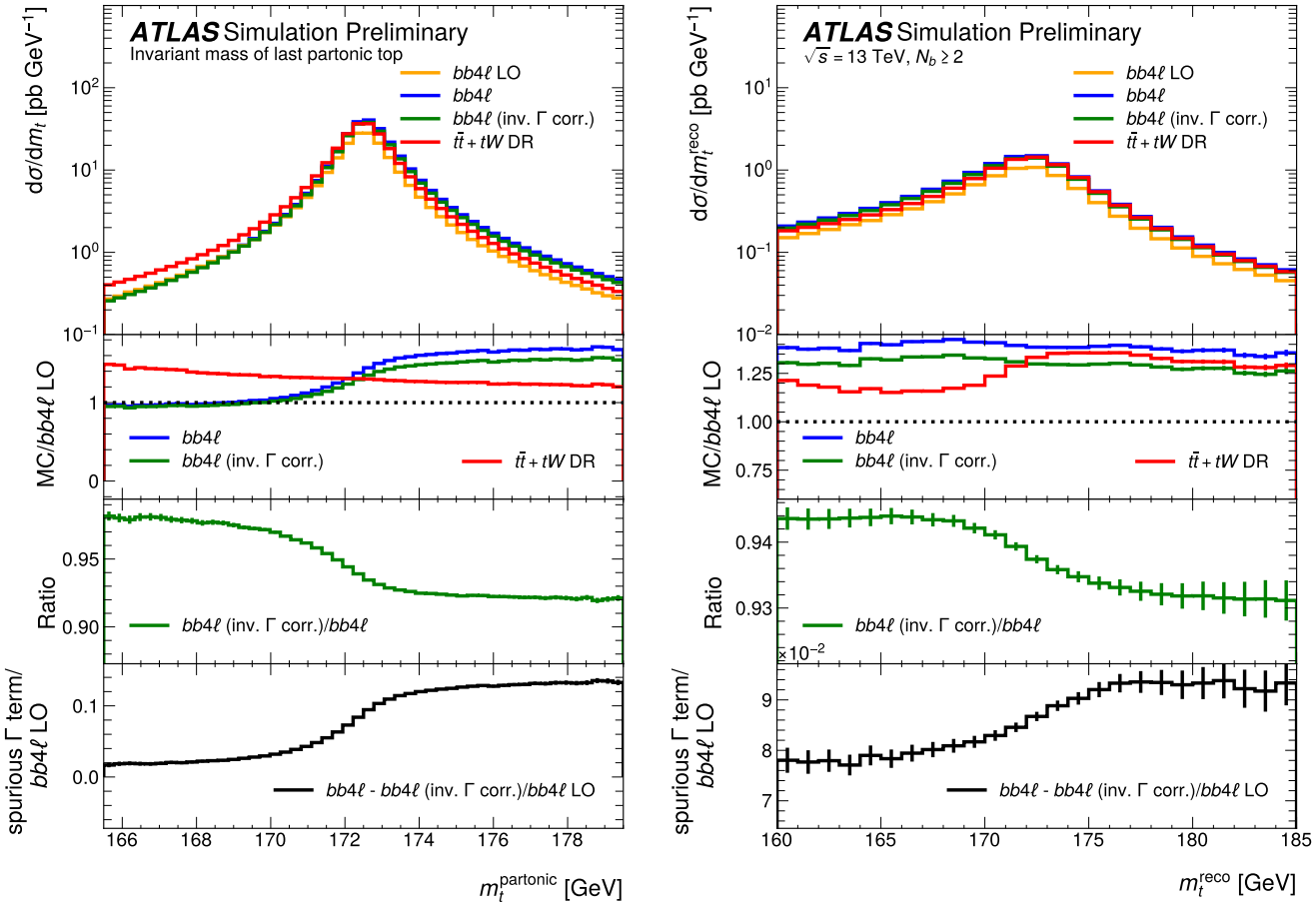
Resonance histories in $bb4\ell$

Output from $bb4\ell$ ME calculation:
initial state + $b\bar{b}\ell^+\nu_\ell\ell^-\bar{\nu}_\ell$ final state
$\rightarrow$ no information about intermediate resonances
! technical issues in POWHEG generation
! recoil distorts m_{inv} of resonances in PS (some analyses need $t\bar{t}$ information)
Resonance history projections
$\rightarrow$ based on $|\mathcal{M}^{\mathrm{LO}}_{t\bar{t}}|^2, \mathcal{M}^{\mathrm{LO}}_{tW\bar{b}}|^2, |\mathcal{M}^{\mathrm{LO}}_{\bar{t}Wb}|^2$





$bb4\ell$ MC sample: inverse width corrections



→ large normalisation effect

→ shape variation in particle-level m_t distribution strongly reduced compared to parton-level m_t