# Differential cross-section measurements of an hadronically decaying $t\bar{t}$-pair produced in association with two b-jets with the ATLAS detector at $\sqrt{s}$ = 13 TeV

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ATLAS EXPERIMENT

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FSP ATLAS

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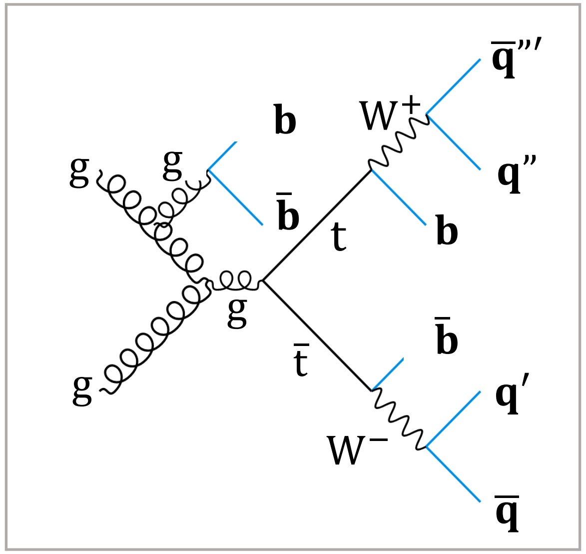
# Analysis introduction

- **analysis aim:** fiducial differential and total cross-section measurements for full Run-2 data (139 $\mathrm{fb}^{-1}$) with the ATLAS detector at $\sqrt{s}$ = 13 TeV
  - **final state of all hadronic $\mathrm{t\bar{t}b\bar{b}}$** characterized by **8 jets in the final state (4 among them are b-jets)**
  - **main backgrounds: multi-jet and all hadronic $\mathrm{t\bar{t}}$**
  - **motivation:**
    - study **dynamics of heavy quark production**
    - **main background of $\mathrm{t\bar{t}H}$ process:** large uncertainties associated to the $\mathrm{t\bar{t}b\bar{b}}$ modeling
- total and differential fiducial $\mathrm{t\bar{t}b\bar{b}}$ cross-section measurement by ATLAS in 2019 in dilepton- and lepton+jets decay-channel [JHEP 04 (2019) 046]
- total all hadronic $\mathrm{t\bar{t}b\bar{b}}$ cross-section measurement by CMS in 2020: $\sigma_{\mathrm{t\bar{t}b\bar{b}}}^{\text{all had}} = 5.5 \pm 0.3\,(\text{stat.})^{+1.6}_{-1.3}\,(\text{syst.})\ \text{pb}$ [Phys. Lett. B, Vol. 803 (2020) 135285]

$$\mathrm{pp} \rightarrow \mathrm{t\bar{t}b\bar{b}} \rightarrow \mathrm{b\bar{q}q'\bar{b}q''\bar{q}'''b\bar{b}}$$



(one possible example of the final-state)

→ **this analysis is the first ATLAS + first all hadronic $\mathrm{t\bar{t}b\bar{b}}$ differential cross-section measurement**

# Event-selection based on MC-events

| process | MC-sample |
|---|---|
| all hadronic $t\bar{t}b\bar{b}$ | Powheg+Pythia8 |
| multi-b | Pythia8 with 4b-filter |
| all hadronic $t\bar{t}$ | Powheg+Herwig7 |

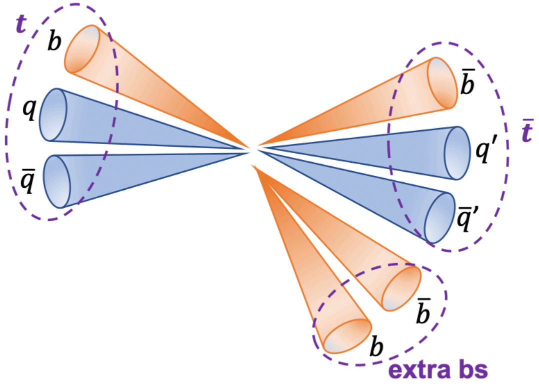
| cut | expected events | | |
|---|---|---|---|
| | $t\bar{t}b\bar{b}$ | mj(4b) | allhad. $t\bar{t}$ |
| quality cuts (GRL etc.) | 2376640.0 | 7649400.0 | 46627700.0 |
| no double counting of $t\bar{t}b\bar{b}$ events in $t\bar{t}$ sample | 2376640.0 | 7649400.0 | 42873800.0 |
| no events with large mc-weight | 2376810.0 | 7649400.0 | 42873800.0 |
| no electron with $p_T \geq 25$ GeV | 2376070.0 | 7646500.0 | 42865300.0 |
| no muon with $p_T \geq 25$ GeV | 2375750.0 | 7646010.0 | 42861300.0 |
| MET $<$ 60 GeV | 1933610.0 | 6180100.0 | 36581600.0 |
| $\geq 8$ jets with $p_T \geq 25$ GeV | 338726 | 269826 | 2807320.0 |
| pass offline 2b2j trigger cuts | 81632.5 | 103171 | 299111 |
| pass online 2b2j trigger | 74381.9 | 96019.8 | 259118 |
| KLFitter-LLH $\geq$ - 50 | 64779.2 | 57720.3 | 237008 |
| | (~ 3%) | (~ 7‰) | (~ 5‰) |

2 b-jets (DL1r 60% WP) with $p_T > 55$ GeV and $\geq 2$ additional jets with $p_T > 55$ GeV

'2b2j'-trigger requires: 4 jets with $p_T \geq 35$ GeV (2 of them need to be b-tagged)

The analysis uses **Particle-Flow** ('PFlow') **jets,**
jets containing a b-hadron (**'b-tagged jets**'/**'b-jets'**) are identified using a neural network, **DL1r.**

# Reconstruction of the all hadronic $t\bar{t}b\bar{b}$ system




- **full reconstruction** of the top-quark and extra b-quark momenta
  → not trivial as jets cannot be associated uniquely with the partons of the hard-scattering process
  → reconstruction algorithms are used to find the best corresponding match between them

- all hadronic $t\bar{t}$ system:
  - use a likelihood-based method for kinematic fitting '**KLFitter**'
    [Nucl. Instrum. Meth. A748 (2014) 18–25, Nucl. Instrum. Meth. A748 (2014) 18–25]
    → extended by us to allow reconstruction for events with ≥ 6 jets in the final-state
  - $\varepsilon_{\mathrm{matched}} = \frac{N_{\mathrm{KLF}}\ \mathrm{output\ does\ match}}{N_{6\ \mathrm{jets\ in\ the\ event\ match}}} \approx 32\%$

- extra bs:
  - **order** the remaining b-jets in the event (not selected by KLFitter) **according to their b-tagging score and choose the two b-jets with highest score**
  - b-jets with same b-tagging score are ordered in $p_T$

# ABCD-method

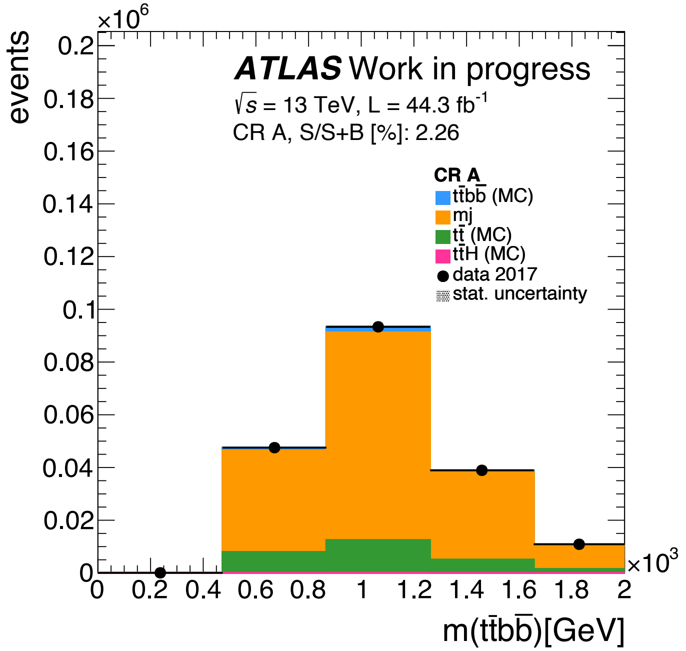
- **ABCD-method is a standard technique for data-driven estimation of the multi-jet background**
  - input: two uncorrelated variables
  - then: definition of 4 regions (3 CRs and 1 SR)

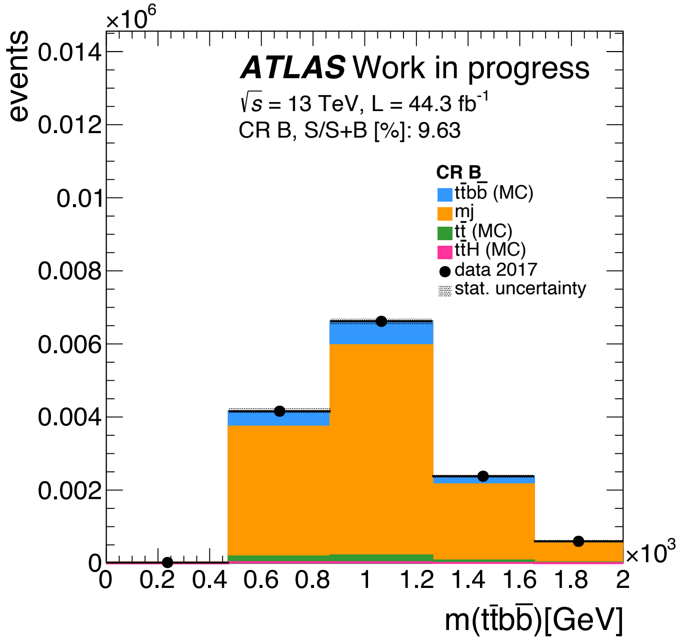
| | $N_b^{85} < 4$ AND $N_{ex\,b}^{85} < 2$ AND $N_b^{60} \geq 2$ | $N_b^{85} \geq 4$ AND $N_{ex\,b}^{85} \geq 2$ AND $N_b^{60} \geq 2$ |
|---|---|---|
| $R_{32}$ outside | **CR A** | **CR B** |
| $R_{32}$ inside | **CR C** | **SR D** |

- **variables** in this analysis
  - $\mathbf{R_{32} = \frac{m_{jjj}}{m_{jj}}}$ [JHEP 09 (2017) 118]
    → $R_{32}$ inside: $R_{32} \in [1.8, 2.4]$ for both tops
    → $R_{32}$ outside: $R_{32} \notin [1.8, 2.4]$ for at least 1 top
  - **number of b-jets** (b) **and extra b-jets** (ex. b) at b-tagging working points with 60%/85% efficiency
    → $N_b^{85} \geq 4$ AND $N_{ex\,b}^{85} \geq 2$ AND $N_b^{60} \geq 2$
    → $N_b^{85} < 4$ AND $N_{ex\,b}^{85} < 2$ AND $N_b^{60} \geq 2$
- **'bin-wise' ABCD method** to obtain bin contents $n_i^{SR\,D}$ of multi-jet distribution in SR D: $n_i^{SR\,D} = \frac{\mathbf{n_i^{CR\,B}}}{\mathbf{n_i^{CR\,A}}} * n_i^{CR\,C}$
- **performs well: good agreement with data** (see next slide)

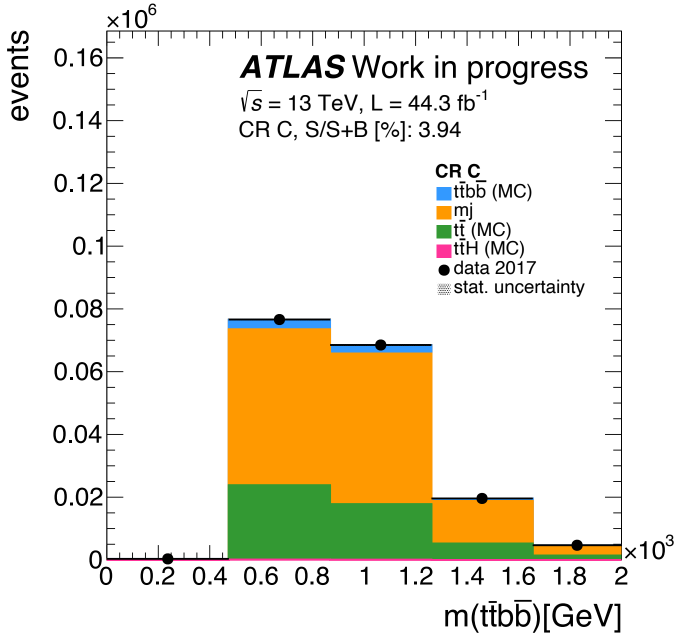
## m(tt̄bb̄)

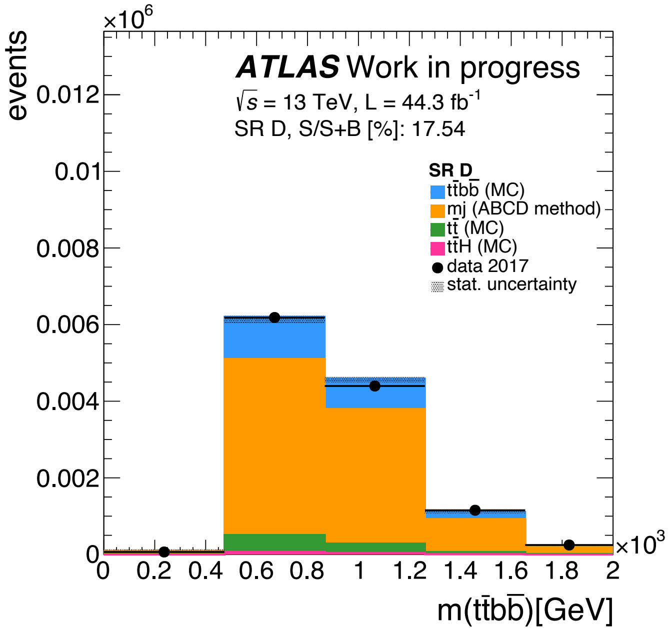
$R_{32}$ outside




$R_{32}$ inside




$N_b^{85} < 4$ AND $N_{ex\,b}^{85} < 2$ AND $N_b^{60} \geq 2$

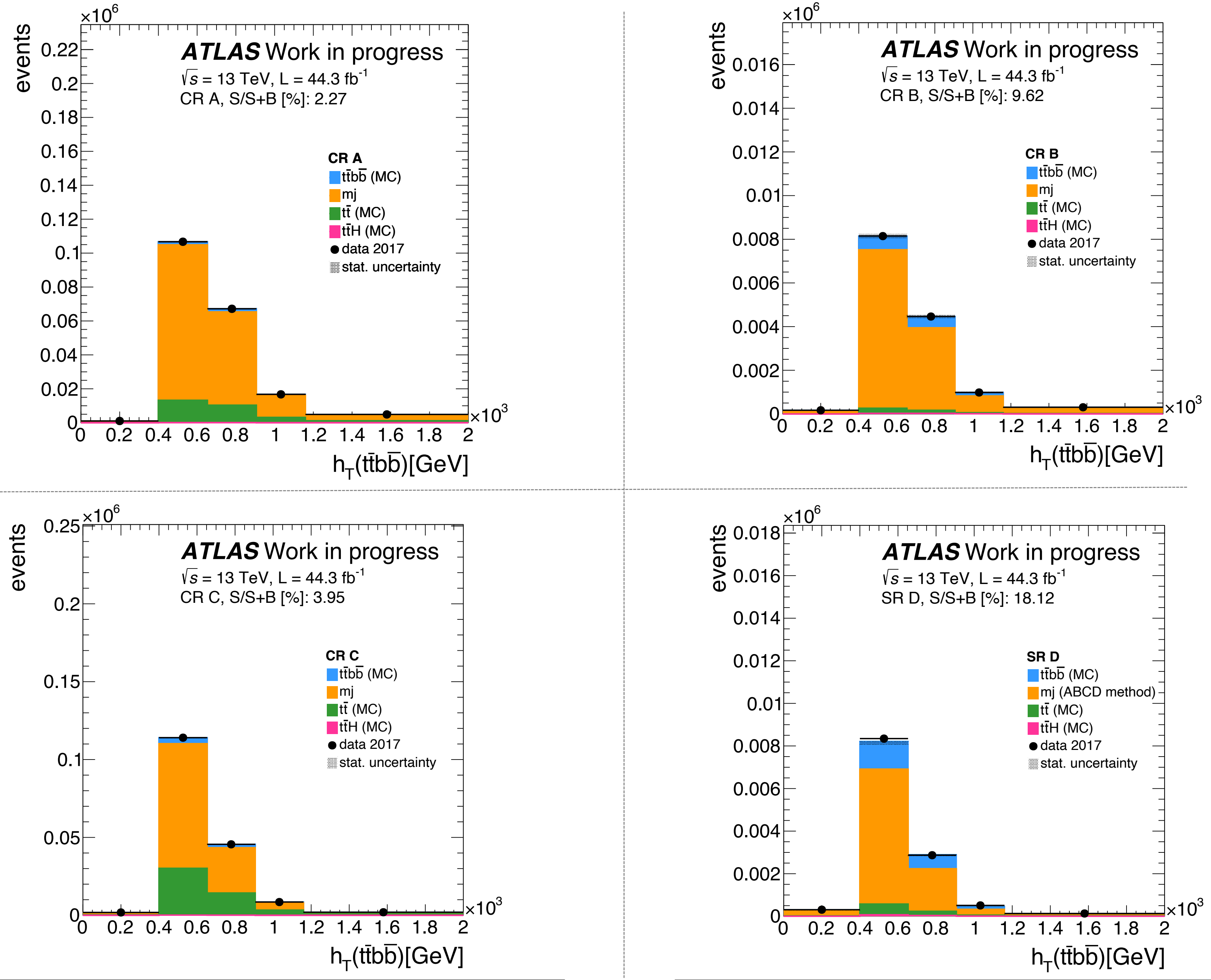
$N_b^{85} \geq 4$ AND $N_{ex\,b}^{85} \geq 2$ AND $N_b^{60} \geq 2$

- expected events from simulation (stack plots) compared to 2017 data
- signal-to-background ratio with
  S = $t\bar{t}b\bar{b}$ MC events
  B = $\sum$ bkg. MC events
- <u>result:</u> good data-MC agreement

## $h_T(t\bar{t}b\bar{b})$

$R_{32}$ outside

$R_{32}$ inside




$N_b^{85} < 4$ AND $N_{ex\,b}^{85} < 2$ AND $N_b^{60} \geq 2$

$N_b^{85} \geq 4$ AND $N_{ex\,b}^{85} \geq 2$ AND $N_b^{60} \geq 2$

- expected events from simulation (stack plots) compared to 2017 data
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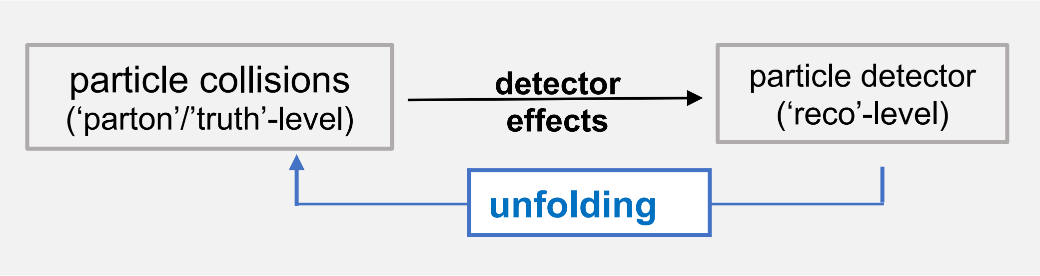
- <u>result:</u>
  good data-MC agreement

# Parton-level unfolding

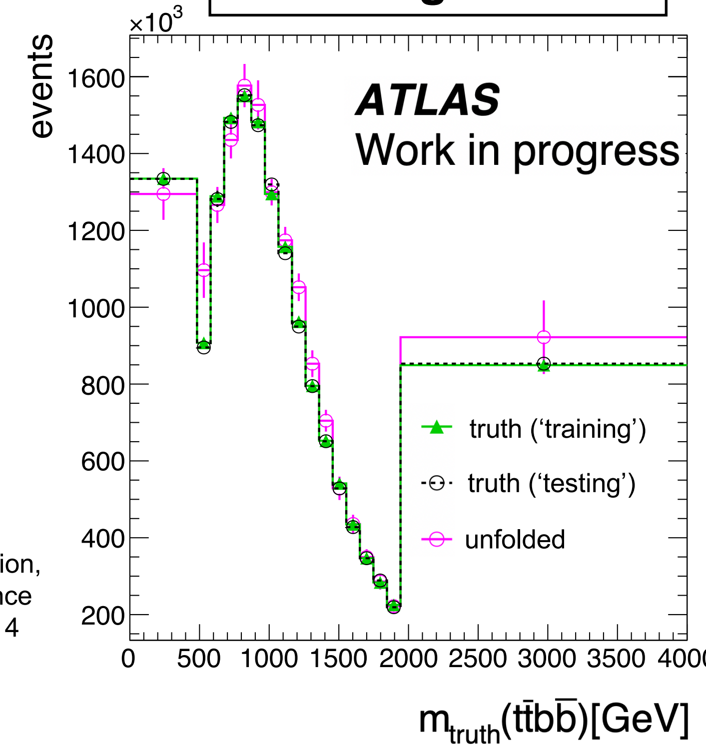



- **unfolding =** infer the parton-information from the distributions measured at detector-level (known to be distorted due to finite resolution and limited acceptance of the detectors)
- **implemented fiducial parton-level unfolding** using Iterative Bayesian Unfolding [NIMA, Vol. 362, Issues 2-3, pp. 487-498 (1995)] as implemented in RooUnfold 2.0.1
- started by looking at $m(t\bar{t}b\bar{b})$, extended to further variables like $h_T(t\bar{t}b\bar{b})$
- conducted multiple studies to ensure **stable and good performance**

**parton-level event-selection**

- $p_T \geq 17.5$ GeV and $|\eta| < 2.9$ for at least **7 partons among all the partons from the $t\bar{t}b\bar{b}$ decay plus the b-quarks from parton shower**
- trigger-mimicing cut: $p_T \geq 48$ GeV for 4 partons and two b-quarkss (top b-quarks, extra b-quarks from parton shower or matrix element bs) $p_T \geq 48$ GeV

**unfolding results**



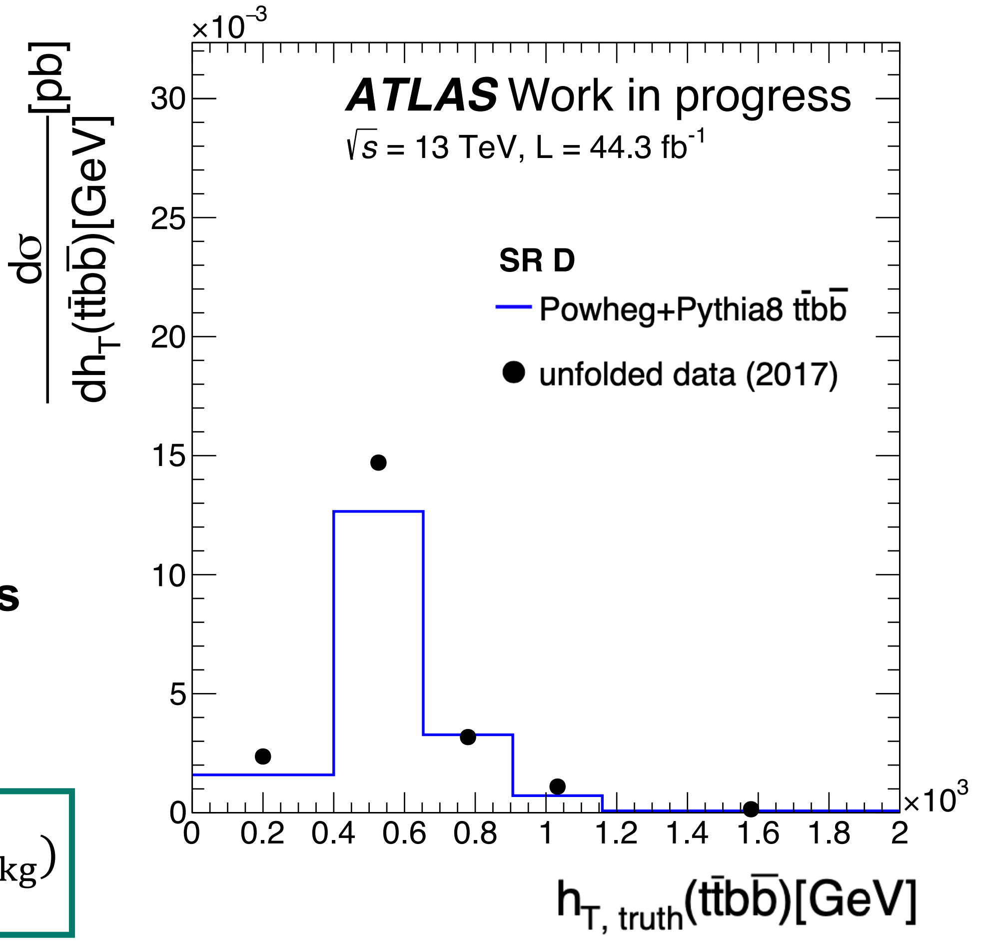

(split-sample, no distortion, with efficiency/acceptance correction, mc-weights, 4 iterations)

# Differential cross-section distribution of $h_T(t\bar{t}b\bar{b})$

**First differential cross-section measurement result:**

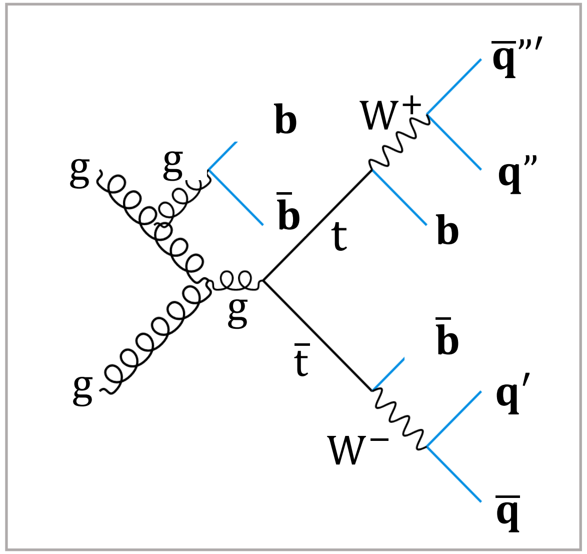
- after unfolding
- trigger efficiency: $f^{i}_{eff,trig} = 0.9$
- unfolding efficiency: $f^{i}_{eff,unf.} = \frac{\sum_i N_i^{reco\&part.}}{\sum_i N_i^{part.}} = 0.01$
- unfolding acceptance : $f^{k}_{acc} = \frac{\sum_i N_i^{reco\&part.}}{\sum_i N_i^{reco}} = 0.88$
- **NO ERRORS shown**
  **→ statistic error calculation for MC work in progress**
  **→ systematic uncertainties work in progress**

$$\frac{d\sigma}{dh_T(t\bar{t}b\bar{b})^i} = \frac{1}{\mathcal{L} * \Delta x^i * f^i_{eff,unf.} * f^i_{eff,trig}} \sum_k \mathcal{M}^{-1}_{ik} * f^k_{acc}(N^k_{data} - N^k_{bkg})$$



# Summary

- presented first preliminary results of **all hadronic $t\bar{t}b\bar{b}$ differential cross-section measurement in ATLAS**
  - **final-state:** 8 jets with 4 b-tagged jets
  - **main backgrounds**: multi-jet and all hadronic $t\bar{t}$
- **reconstruction of all hadronic $t\bar{t}$-system** in $t\bar{t}b\bar{b}$ events performed with **KLFitter**,
  **extra bs** selected according to their **b-tagging score**
- **estimation of multi-jet background with ABCD method**
  → good agreement with MC predictions
- **unfolding** conducted with **Iterative Bayesian Unfolding** as implemented in RooUnfold



(one possible example of the final-state)

- first **differential cross-section measurement in $h_T(t\bar{t}b\bar{b})$** obtained
  → statistical **error calculation and** determination of **systematic uncertainties work in progress**
- **measurement will be extended to further variables**