SM & QCD Workshop, Prague

Large-R jets in boosted top-quark pair production with ATLAS

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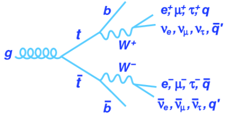
October 8, 2018

Outline

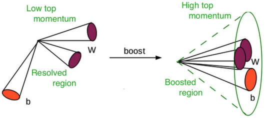
- Introduction
- Measurement of $t\bar{t}$ differential cross-sections in boosted all-hadronic channel
- Large-R jets definitions & properties
- Overview of the measurement

Introduction

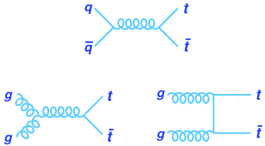
- Top-quark
  - Charge +2/3
  - The heaviest elementary particle
  - Short lifetime - decay almost immediately
  - Leptonic decay: t $\rightarrow$ W$^+$ + b-quark $\rightarrow$ l$^+$ + neutrino + B-hadron
  - Hadronic decay: t $\rightarrow$ W$^+$ + b-quark $\rightarrow$ 2 quarks + B-quark $\rightarrow$ hadrons



- Hadronic top reconstruction
  - Resolved topology:
    - Low top p_{T} $\rightarrow$ top decay products separated
    - Three small-radius jets used to reconstruct individual quarks from decay
  - Boosted topology:
    - High top p_{T} $\rightarrow$ top decay products close to each other
    - Single large-radius jet used to reconstruct all top decay products
    - Effective for top quark $p_{\mathrm{T}} > 300$ GeV



- $t\bar{t}$ production
  - QCD process
  - Similar to Beyond Standard Model processes
  - Sensitive to parton distribution functions and hadronization + parton showering models



Measurement of $t\bar{t}$ differential cross-sections in boosted all-hadronic channel

- ATLAS experiment, 13 TeV, proton-proton collisions, data 2015-2018
- Analysis team:
  - Prague: Roman Lysák, Jiří Hejbal, Petr Jačka
  - Torronto: Kyle Cormier, Riccardo di Sipio, Pekka Sinervo, Bianca Monica Ciungu
- Already published paper with data 2015-2016
  - Measured 1D differential cross-sections

- General features:
  - All-hadronic channel: Both top quarks decay hadronically
  - Very high top p_{T} (Boosted topology)
    - **Two large-R jets** used to reconstruct $t\bar{t}$ system
  - Strong multijet background (QCD)
    - Large-R jet **substructure** and **b-tagging** information used to separate top quarks from background

- Goals:
  - Improve precision of the measurement
  - Extend range of the measured distributions
  - Measure 2D spectra
  - Compare results with SM and BSM predictions

Jet algorithms: part 1

- Only jet clustering algorithms considered
- Input: Set of clusters (4-momenta)
- Output: Set of jets
- $d_{ij} = \min\left[p_{\mathrm{T},i}^{2n}, p_{\mathrm{T},j}^{2n}\right] \cdot R_{ij}^2 \leftarrow$ Distance between clusters
- $d_{iB} = p_{\mathrm{T},i}^{2n} \cdot R_0^2 \leftarrow$ Distance from the beam
- $R_{ij} = \sqrt{(\Delta\eta)_{ij}^2 + (\Delta\phi)_{ij}^2}$
- Fixed R_0: Produce jets with **fixed radius**
- Variable R_0: Variable-R jets, e.g. $R_0 \equiv R_i = \frac{2m_{\text{top}}}{p_{\mathrm{T},i}}$

- kt-algorithm: $n = 1$
  - Used in past
  - Still used as a part of algorithms: jet substructure, pileup removal
- Cambridge-Aachen algorithm: $n = 0$
  - Just angular matching, no care about momentum
  - Good for jet substructure description
- Anti-kt algorithm: $n = -1$
  - Most widely used
  - Very good results at high p_{T} regions

Clustering algorithm:

1. If set of clusters is empty: stop
2. Calculate $\min_{i \neq j} d_{ij} = d_{i_0 j_0}$ and $\min_{i} d_{iB} = d_{i_1}$ variables
3. **if** $(d_{i_0 j_0} < d_{i_1})$: Combine clusters i_0 and j_0 into one cluster
   else: Cluster i_1 is moved to jet collection and removed from the set of clusters
4. Go to 1

- Input: Set of clusters
- Output: Set of jets
- $d_{ij} = \min\left[p_{\mathrm{T},i}^{2n}, p_{\mathrm{T},j}^{2n}\right] \cdot R_{ij}^2 \leftarrow$ Distance between clusters
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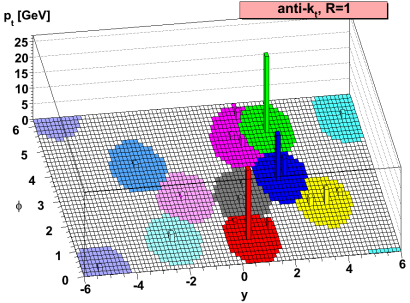


Large-R jet examples

- Anti-kt $R = 1.0$ jets
  - Anti-kt algorithm with fixed radius $R = 1.0$
  - Inputs: Calorimeter clusters (LCTopo)
- Reclustered jets
  - Small radius jets used as inputs for clustering algorithm
    - Anti-kt $R = 0.4$
  - Fixed radius: Anti-kt $R = 1.0$
  - Variable-R: $R_i = 2m_{\text{top}}/p_{\mathrm{T},i}$
    - Limited maximum radius $R = 1.0$
  - Small-R jets calibrated before reclustering
    - No need to calibrate reclustered jets
- Other types
  - Variable-R jets : More effective at very high top p_{T}
  - Different inputs: Particle Flow
  - Alternative pileup removal techniques

Pileup removal techniques

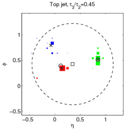
- Large-R jets are heavily influenced by pileup
  - Noise from other other collisions in the same or surrounding bunch crossing
- Goal: Clean jet from pileup and other noise
- Ideal case: Jet 4-momentum independent of number of interactions per bunch crossing
- Trimming algorithm
  - Create set of subjets from the large-R jet constituents
    - kt-algorithm with a small radius R
  - All subjets with $p_{\mathrm{T}} < f \cdot p_{\mathrm{T,Large\text{-}R\ jet}}$ are removed
  - Usually used: subjets with radius $R = 0.2$, $f = 0.05$
- Other algorithms: Prunning, Soft Drop, SoftKiller, ...

Jet substructure variables

- Used to identify large-R jets originating from top hadronic decay
- 3-body decay identification: τ_{32} variable
- W boson in top decay identification: Q_W, split$_{23}$
- High large-R jet mass

τ_{32} definition

- Indentifies how much the jet looks like originating from 3-body decay



- Based on N-subjettiness variable τ_N
  - N directions chosen inside large-R jet (kt-algorithm, WTA scheme)
- $\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T},k} \min\{\Delta R_{1,k}, \ldots, \Delta R_{N,k}\}$
- $d_0 = \sum_k p_{\mathrm{T},k} R_0$
- $\tau_{32} = \tau_3 / \tau_2$

Q_W, split$_{23}$ definition

- kt-algorithm is applied on large-R jets constituents
- Stopped when exactly 3 subjets remain - ordered by p_T
- $Q_W = \min[m_{12}, m_{13}, m_{23}]$
  - Represents W-boson invariant mass
- Split$_{23} = \min[p_{\mathrm{T},2}, p_{\mathrm{T},3}] \cdot R_{23}$
  - Identifies W-boson 2-body decay

Overview of the measurement

- Started this year
- Aim to present results on Top2019 conference, September 2019
- Data:
  - ATLAS detector, 2015-2017, 80 fb^{-1}
  - Data 2018 will be included soon
- Monte Carlo samples
  - Powheg+Pythia8 used as nominal sample for $t\bar{t}$ production
  - Samples with different generators combinations under production
  - High MC statistics samples under production

Event selection

- Large-R jets ordered by their p_{T}
- Several jet types tested

- Pre-selection: Same for all large-R jets types
  - At least two large-R jets with $|\eta| < 2.0$
  - 1st large-R jet $p_{\mathrm{T}} > 500$ GeV
  - 2nd large-R jet $p_{\mathrm{T}} > 350$ GeV
  - Mass window cuts around top mass
    - 1st large-R jet $|m - 172.5| < 50$ GeV
    - 2nd large-R jet $|m - 172.5| < 50$ GeV
  - At least two small-R jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$
    - Anti-kt $R = 0.4$
    - B-tagging information carriers

- Top-tagging and B-tagging of the leading two large-R jets
  - Depends on large-R jets definitions
  - Top-tagging: based on large-R jets substructure
  - B-tagging: Information taken from small-R jets
  - Several top-taggers and b-taggers are tested

Top-tagging and b-tagging

- Anti-kt $R = 1.0$ jets
  - Top-tagging
    - Two possibilities tested
    - Mass and Tau32 based top tagger, simple p_{T} dependend cuts
    - Deep neural network (DNN) top tagger
  - B-tagging: Geometrical matching with b-tagged small-R jets
- Reclustered jets
  - Top-tagging: Mass and Tau32 based tagger, p_{T} dependend cuts
    - Optimized for standard anti-kt $R = 1.0$ jets
  - B-tagging: At least one subjet is b-tagged
- Variable-R reclustered jets
  - Top-tagging
    - Substructure variables not yet available
    - Tagging based on invariant mass of subjets - not effective
  - B-tagging: At least one subjet is b-tagged

Selected events composition

Signal	6409 ± 69
Multijet	938 ± 23
$t\bar{t}$ non-allhad	215.8 ± 7.8
ttX, X=H,W,Z	66.3 ± 1.5
Wt single-top	40.3 ± 3.3
All background	1261 ± 24
Prediction	7670 ± 73
Data	6662 ± 82
Data / Pred.	0.87 ± 0.01

- Event yields for Anti-kt $R = 1.0$ large-R jets
- DNN top tagger
- Only stat. uncertainties shown

- Prediction = Signal + All background
- Signal is dominant
  - Signal/Prediction $\sim$ 0.84
- Multijet background:
  - Dominant background contribution
  - QCD processes without top-quarks
  - Hadronic W boson + jets production
  - Determined using data-driven technique: **ABCD method**
  - Multijet/Prediction $\sim$ 0.12
- Other relevant backgrounds:
  - $t\bar{t}$ production: single-lepton and di-lepton channel
  - ttX processes: X = H,W,Z
  - Single-top: Wt channel
  - Contribution determined using MC simulated events
- Data/Prediction = 0.87
  - Too many predicted events

Reco level plots

- Data compared with overall predictions
- Monte Carlo simulated events include full detector simulation (GEANT4)

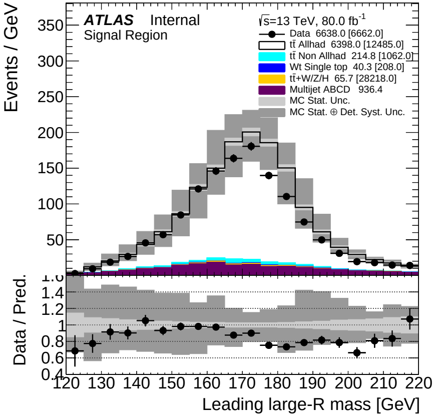
- Uncertainties
  - From limited data statistics
  - From limited MC statistics
  - Detector systematics
    - Incomplete: some sources are missing
    - Calibrations of objects are not finalized
  - Signal modeling systematics missing
  - Background modeling
    - Only variation of cross-sections of background sources

Plots organization

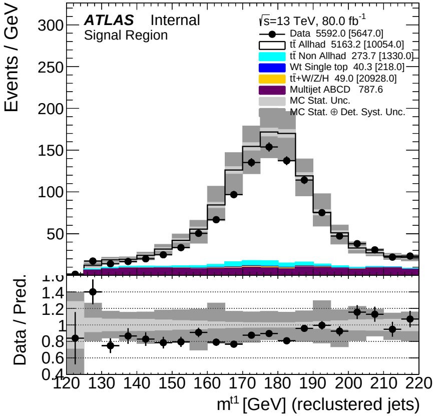
Anti-kt $R = 1.0$ jets
DNN top-tagger

Reclustered $R = 1.0$ jets
τ_{32} and mass based top-tagger

Reco level plots: Leading large-R jet mass



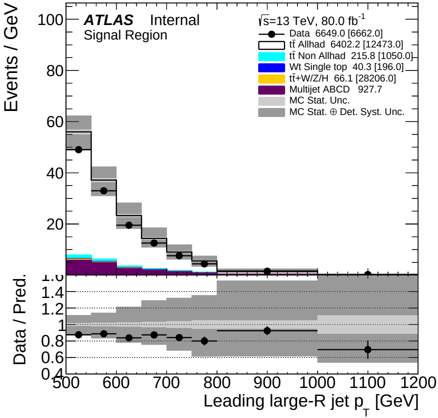
Anti-kt $R = 1.0$ jets



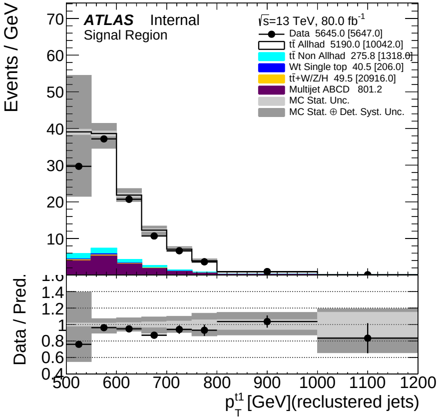
Reclustered $R = 1.0$ jets

- Small differences between data and prediction
- Anti-kt $R = 1.0$ jets: Peak shifted from data
- Reclustered jets: Slope in ratio plot

Reco level plots: Leading large-R jet p_{T}



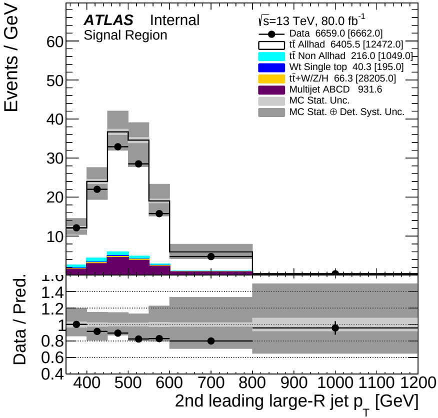
Anti-kt $R = 1.0$ jets



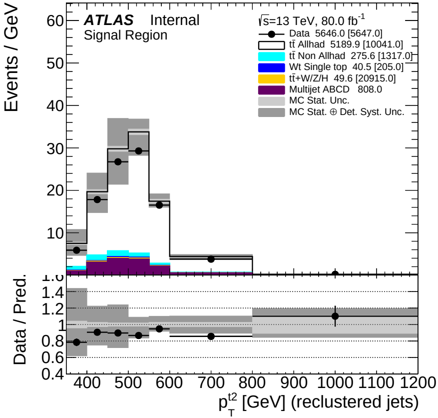
Reclustered $R = 1.0$ jets

- Sensitive to order of the matrix element calculation
- Significantly larger uncertainties for Anti-kt $R = 1.0$ jets
  - Overestimated
- Good agreement between data and prediction

Reco level plots: 2nd leading large-R jet p_{T}



Anti-kt $R = 1.0$ jets



Reclustered $R = 1.0$ jets

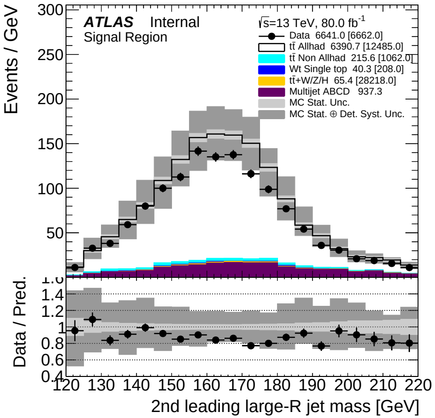
- Anti-kt $R = 1.0$ jets: Slope in Data/Prediction ratio

Summary & next steps

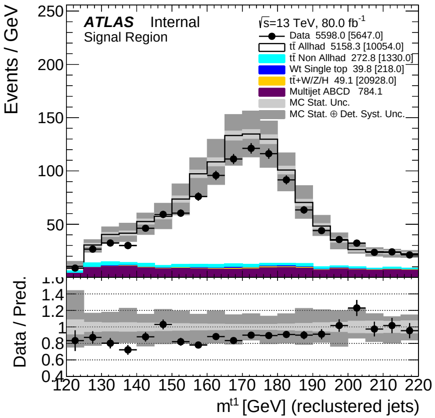
- Summary
  - Work in progress results of the measurement are presented
  - Two large-R jet types compared
    - Small differences between distributions observed
    - Uncertainties may be smaller for reclustered jets
  - Still lot of work to do
  - Aim to present results on Top2019 conference, September 2019
- Next steps
  - Determine all uncertainties
  - Compare jet types and choose the best one
  - Optimize top-taggers
  - Measure 2D spectra
  - Unfolding: Correct for detector effects
  - Compare measured spectra with SM and BSM predictions

Backup

Reco level plots: 2nd leading large-R jet mass



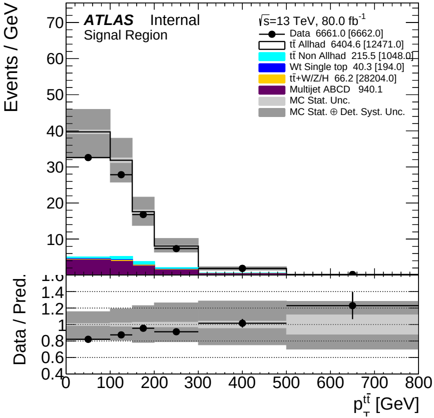
Anti-kt $R = 1.0$ jets



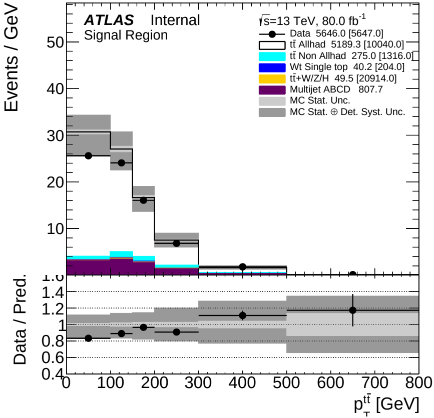
Reclustered $R = 1.0$ jets

- Anti-kt $R = 1.0$ jets: Peak shifted to the left from top mass
- Reclustered jets: Peak around top mass

Reco level plots: $t\bar{t}\ p_{\mathrm{T}}$

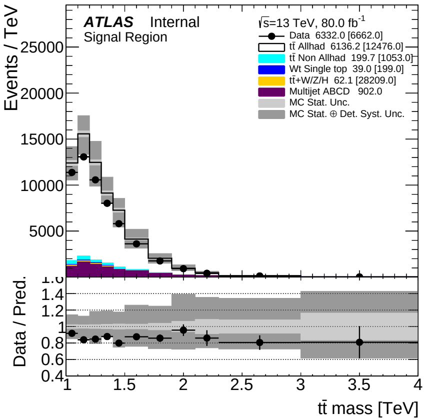


Anti-kt $R = 1.0$ jets

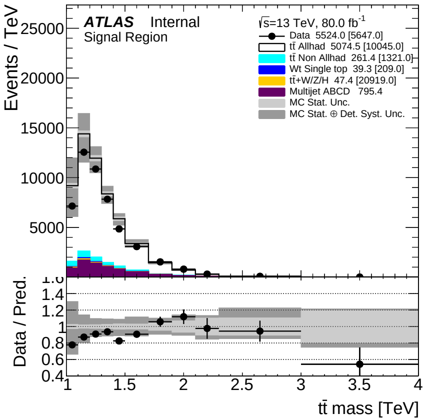


Reclustered $R = 1.0$ jets

Reco level plots: $t\bar{t}$ mass



Anti-kt $R = 1.0$ jets



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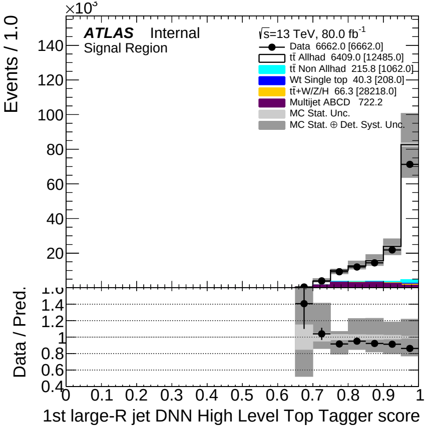

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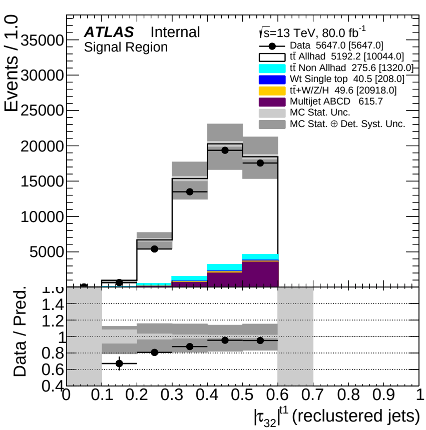
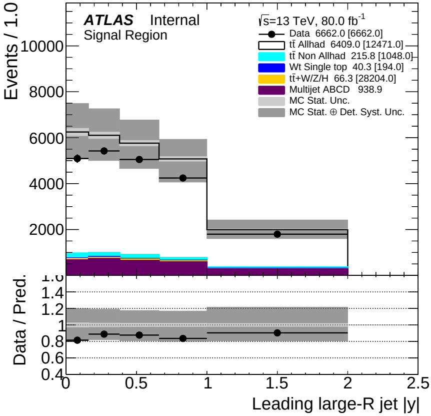
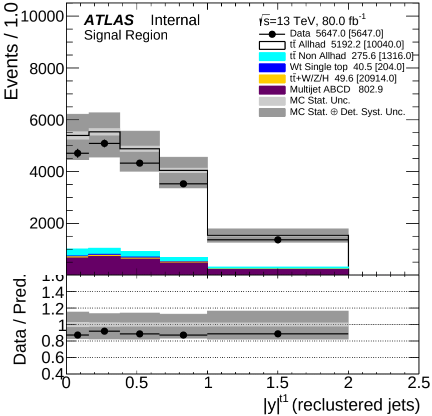


Reclustered $R = 1.0$ jets

Reco level plots: Leading large-R jet rapidity

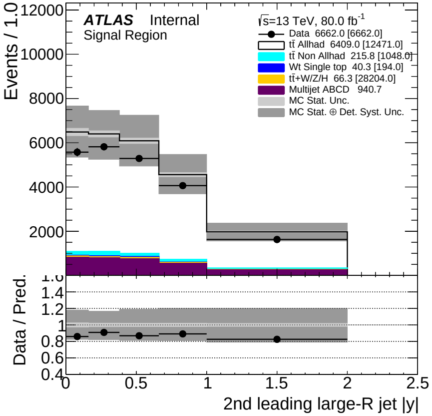


Anti-kt $R = 1.0$ jets

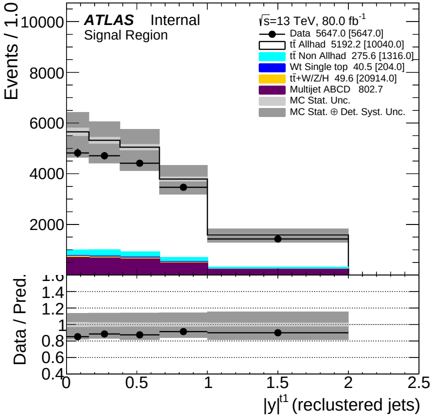


Reclustered $R = 1.0$ jets

Reco level plots: 2nd leading large-R jet rapidity



Anti-kt $R = 1.0$ jets



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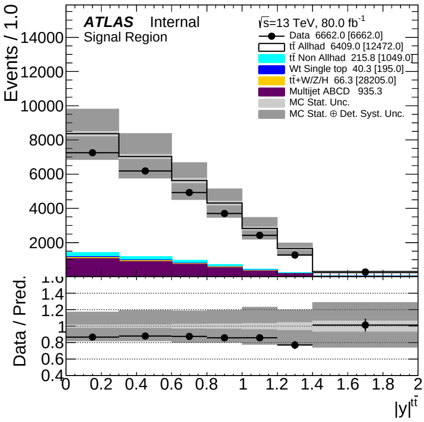

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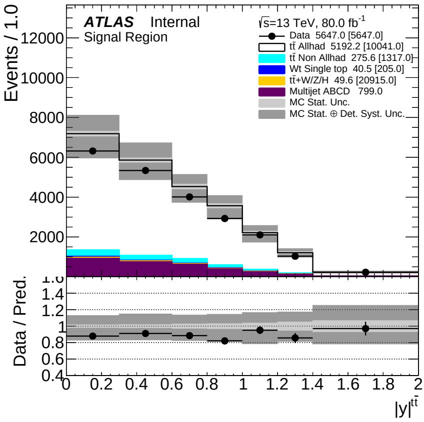

Reclustered $R = 1.0$ jets