Measurements of $t\bar{t}$ differential cross-sections using highly-boosted top quarks decaying to the all-hadronic channel in pp collisions at $\sqrt{s}$=13 TeV using the ATLAS detector

Kyle Cormier on behalf of the ATLAS Collaboration

Measurement Overview

- Full $t\bar{t}$ event kinematic reconstruction from **high-p_T** large-R jets

- Absolute and normalized **differential cross-sections** for 13 kinematic observables unfolded to **fiducial particle-level phase space.** Results unfolding to a **limited parton-level phase space** are also in progress.

- Full 2015 + 2016 ATLAS 13 TeV proton-proton collisions dataset with total integrated luminosity of **36.1 fb^{-1}**.

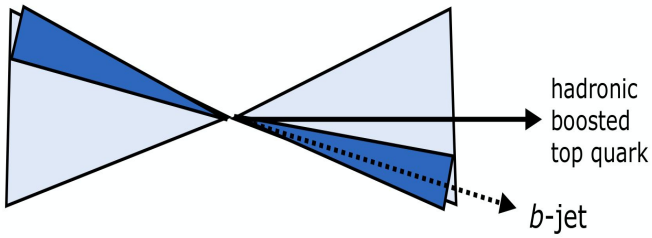
- Predict 3250 signal events and 1070 background events in final selection

Event Selection

- **2 Anti-k_T R = 1.0** ("Large-R") jets with high p_T and $|\eta| < 2.0$
  - Jet mass within 50 GeV of top-quark mass
  - Leading jet **p_T > 500 GeV**
  - Second-leading jet **p_T > 350 GeV**
- 2 Anti-k_T R = 0.4 ("small-R") jets with $p_T > 25$ GeV and $|\eta| < 2.5$
- No isolated electrons or muons with $p_T > 25$ GeV and $|\eta| < 2.5$

"Pre-selection" used for background determination

- Large-R jets are both **top-tagged**
- Large-R jets both have **b-tagged small-R jet** within R < 1.0 ("b-matched")



B-tagging:
Boosted Decision Tree based tagger with 70% nominal efficiency

Top-tagging:
Cut on N-subjettiness τ_{32} and jet mass

Cut values change as a function of p_T to achieve a flat 50% efficiency

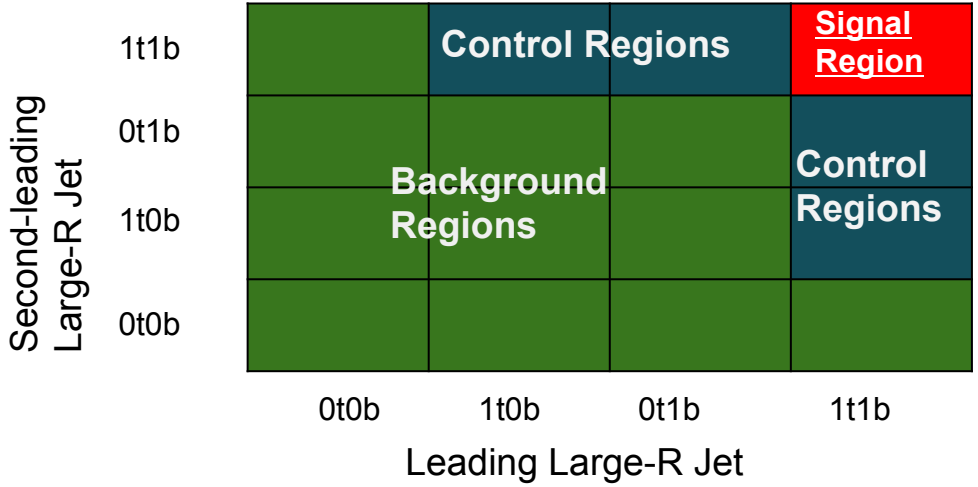
Backgrounds

- Dominated by QCD processes with no top quarks (“multijet”)
  - Estimated from data
- Smaller contributions from non all-hadronic $t\bar{t}$, single-top, and $t\bar{t}$+H/W/Z
  - Estimated using Monte-Carlo

Multijet Estimation:

- ABCD method performed using pre-selection events divided into 16 categories based on large-R jet top-tagging and b-matching.

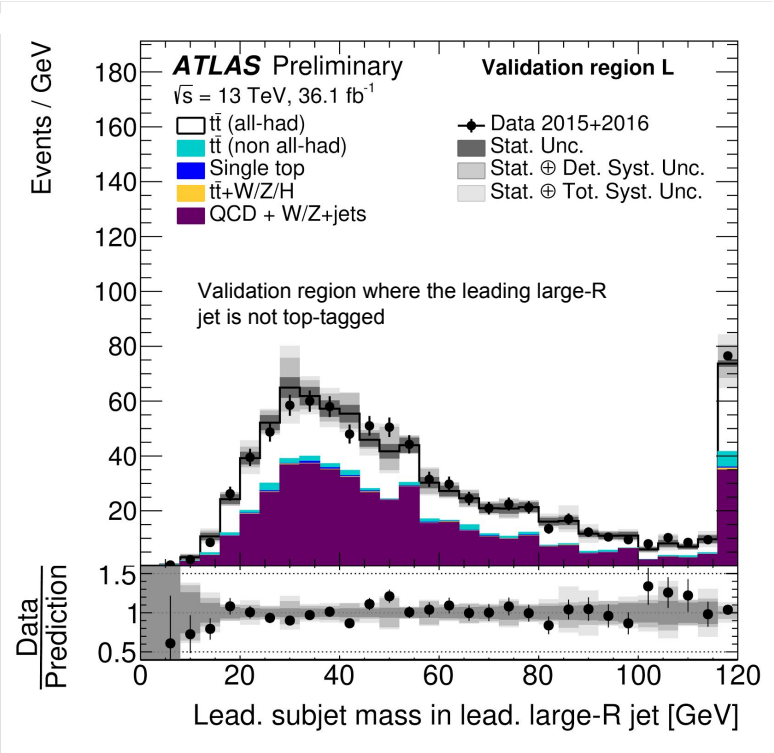
  - Subtract signal and backgrounds estimated with Monte Carlo
  - Estimate signal and control region distributions from ratios of distributions in background regions



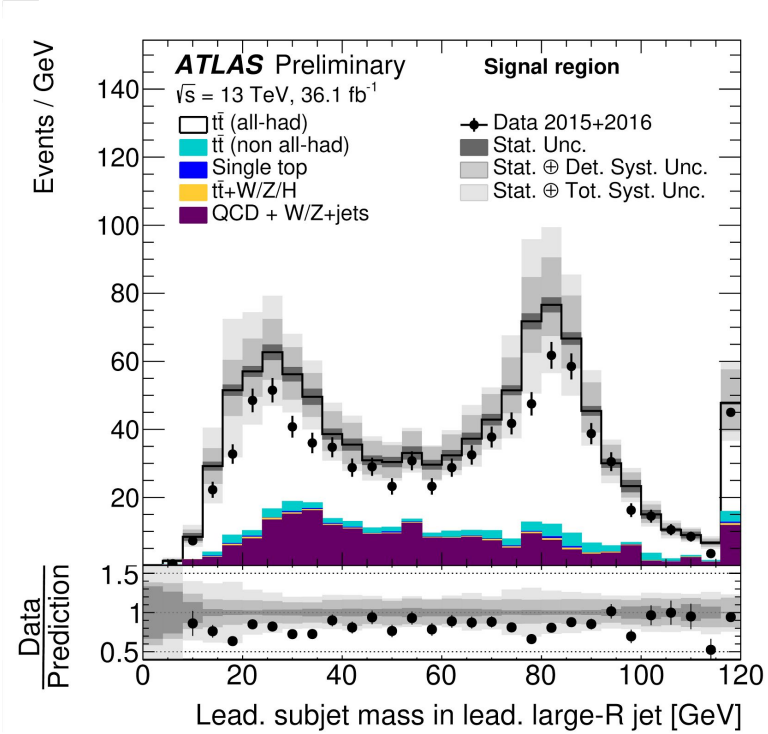
More Details in backup

Detector-level Plots

Validation regions are well described.



W mass peak clearly visible in subjet mass distribution, good signal region purity



Phase Space Definitions and Unfolding

- Data is unfolded back to stable particle level and parton level phase space
- Phase-Spaces chosen to match detector-level event selection and minimize extrapolation to unmeasured regions
- Use iterative Bayesian unfolding method with 4 iterations

<u>Particle level fiducial phase space</u>

- All-hadronic $t\bar{t}$ event
- **2 Anti-k_T R = 1.0 jets** with $|\eta| < 2.0$
  - Leading jet **p_T > 500 GeV**
  - Second-leading jet **p_T > 350 GeV**
  - Both associated with B-hadron via ghost-matching
  - Masses within 50 GeV of top quark mass (172.5 Gev)

- 2 Anti-k_T R=0.4 jets with $p_T > 25$ GeV and $|\eta| < 2.5$
- No dressed electrons or muons with $p_T > 25$ GeV and $|\eta| < 2.5$

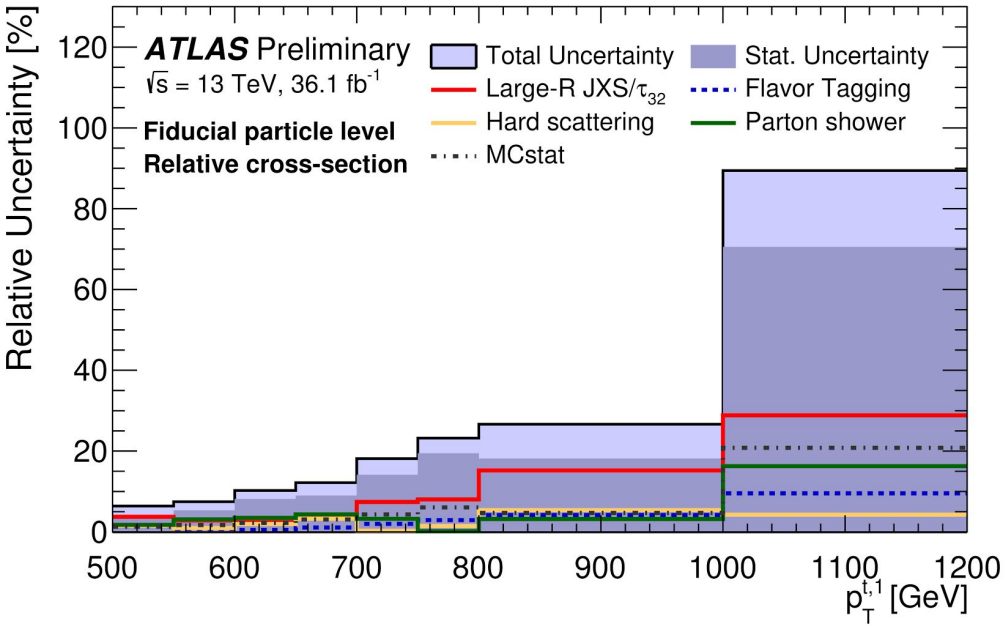
<u>Parton level restricted phase space</u>

- $t\bar{t}$ event
- Leading top quark **p_T > 500 GeV**
- Second-leading top quark **p_T > 350 GeV**

Unfolding details: in backup

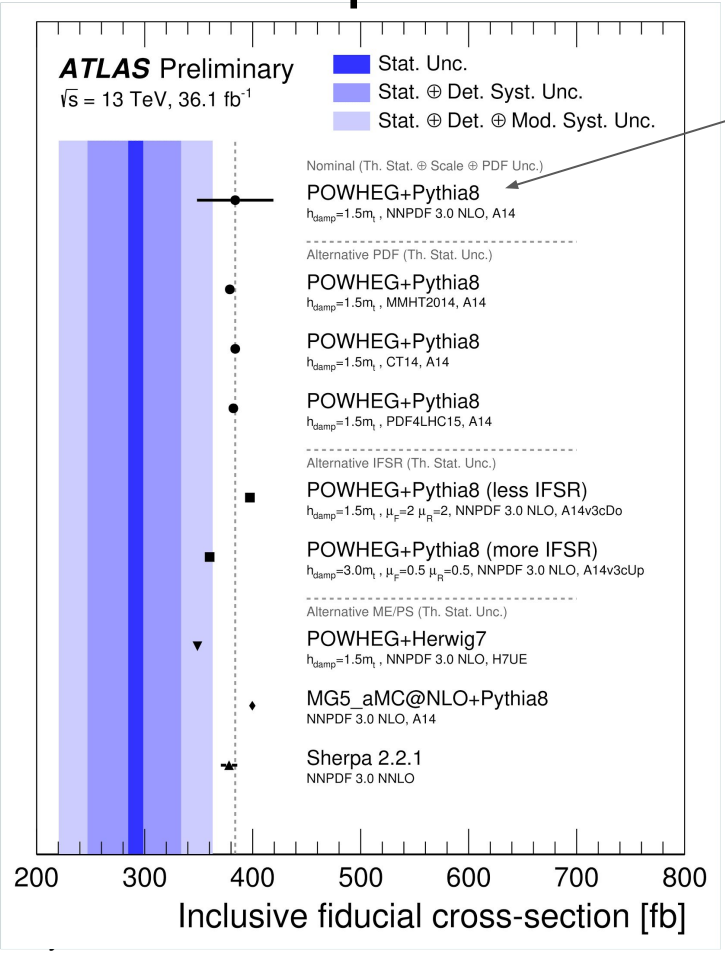
Uncertainties

- Detector systematics and statistical uncertainties assessed using pseudo-experiments before unfolding.
  - Account for correlation introduced by unfolding
- Modelling uncertainties account for sensitivity of unfolding procedure to assumed physics model.
  - Large differences in τ_{32} description are particularly impactful
  - Assessed comparing various Monte Carlo samples output to their own unfolded estimate.



Measurement uncertainties explicitly showing the dominant sources of systematic uncertainty

Results - particle-level fiducial cross-section



Nominal prediction used to correct for detector effects. Uncertainties on for this point include PDF and scale variations†. All other predictions include only statistical uncertainties.

Measured fiducial cross-section

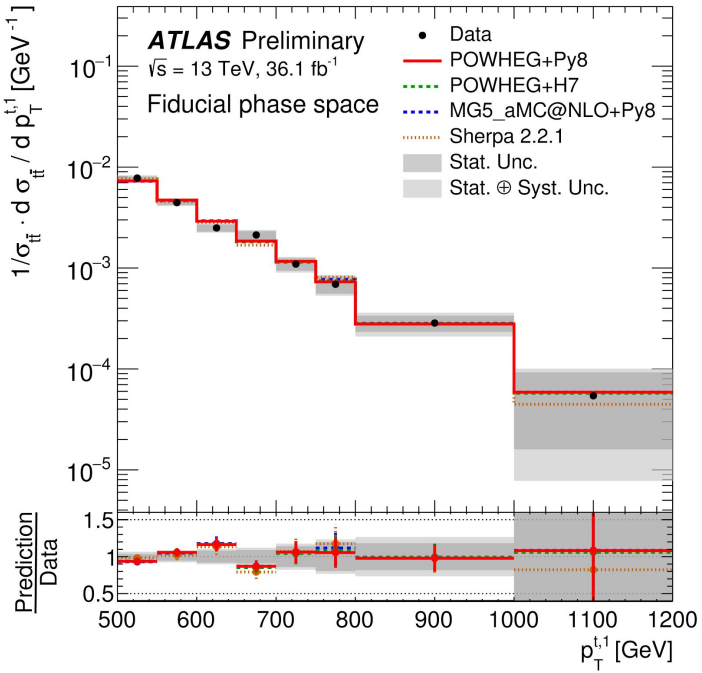
292 ±7 (stat) ±76 (syst) fb

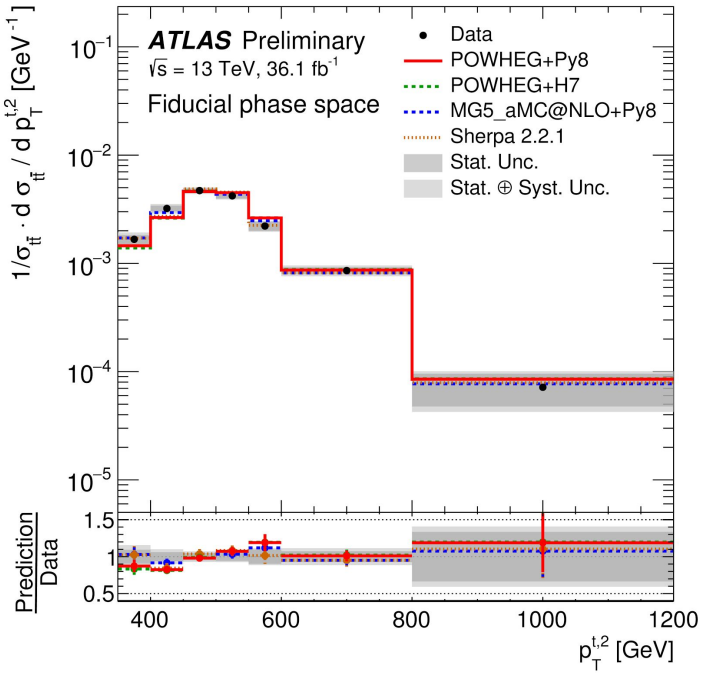
- All predictions are above the measured cross-section by O(30%) corresponding to a significance of ~1σ.
- Improved understanding of $t\bar{t}$ modelling and detector response are the key to future improvements

† PDF uncertainties are obtained using the PDF4LHC recommendations with 30 eigenvectors. Scale uncertainties are obtained by taking the envelope of obtained by varying the renormalization and factorization scale independently in the range 0.5-2.0. The two uncertainties are then summed in quadrature.

Results - top quark observables (normalized)

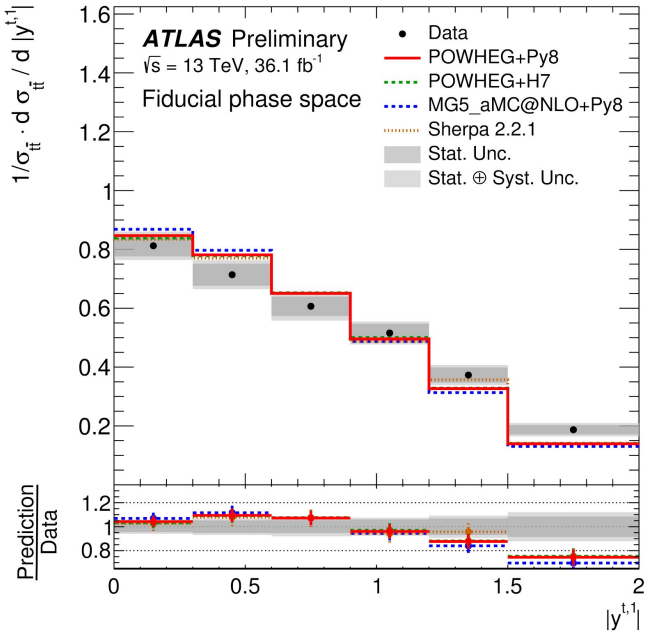
Top quark p_T shapes modelled very well by Monte Carlo

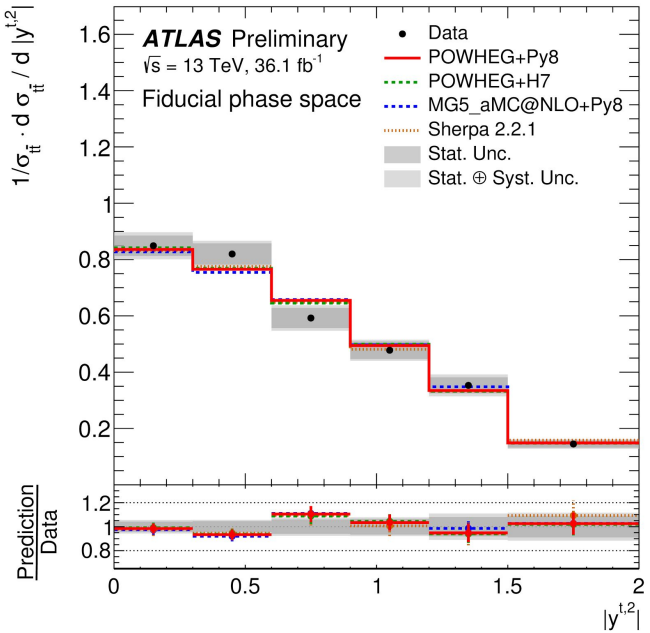




Results - top quark observables (normalized)

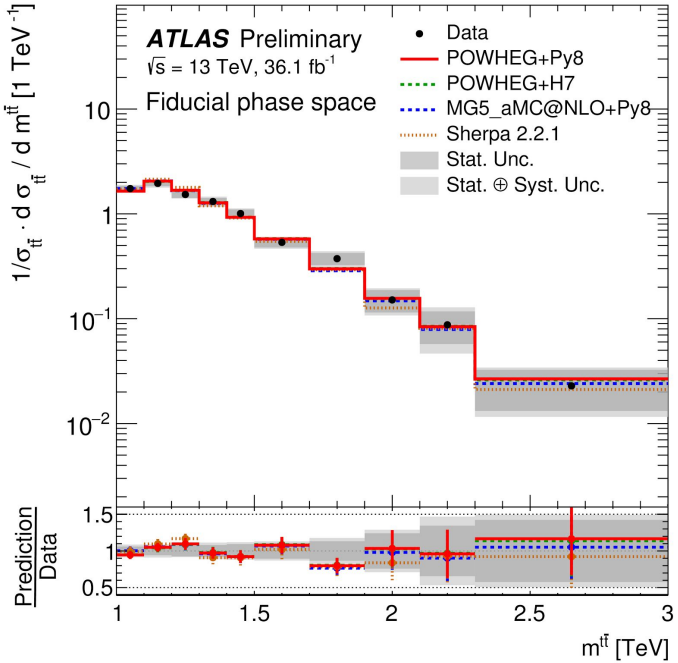
- Subleading top rapidity described very well
- Leading top rapidity predictions are consistent with the measurement, though the central values show a slope as compared to the measurement

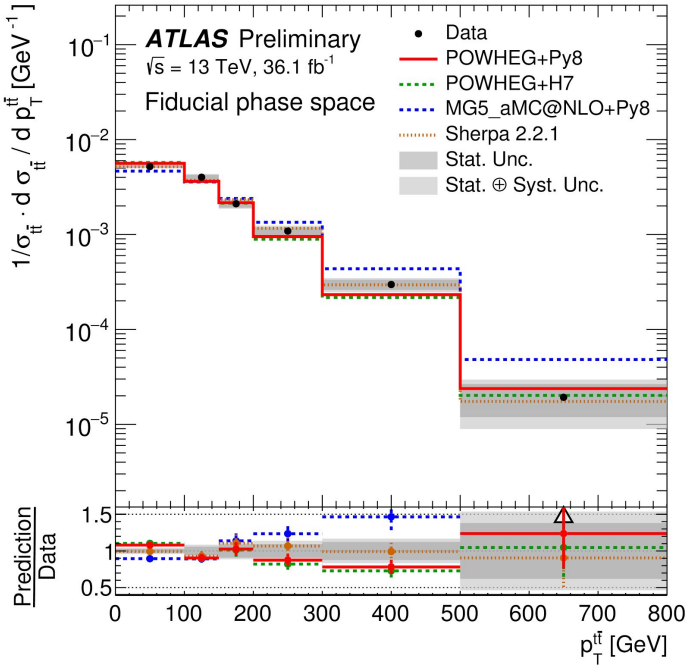




Results - $t\bar{t}$ system observables (normalized)

aMC@NLO + Pythia8 setup shows some discrepancies in modelling $t\bar{t}$ system kinematics sensitive to extra radiation





Summary

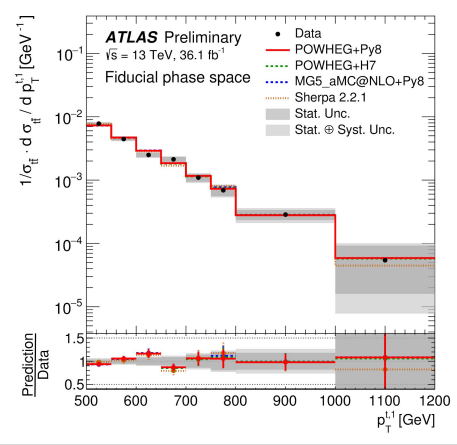
- Unfolded measurement of boosted $t\bar{t}$ differential cross-sections in the all-hadronic channel with the ATLAS detector

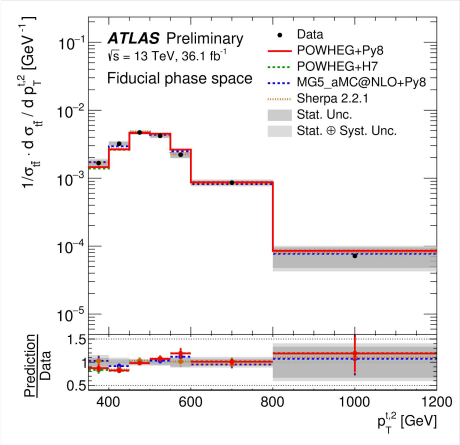
- More than 3000 events in the signal region, and signal to background of 3:1

- Next-to-Leading Order Monte Carlo generators predictions agree with the measurement within uncertainties

- Some trends in central values are non-statistical in nature; a better understanding of tagging performance, modelling and their effects on unfolding will help to improve future measurements.

BACKUP


ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σtt · d σtt / d pT t,1 [GeV-1]
Prediction / Data
pT t,1 [GeV]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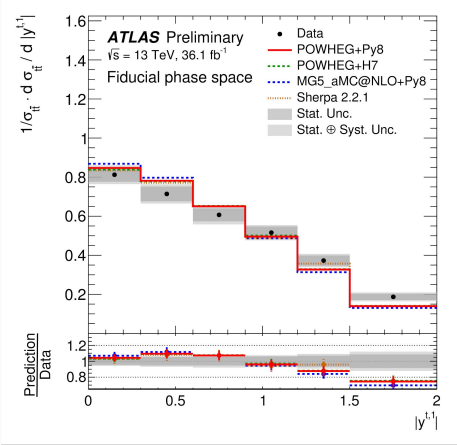
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σtt · d σtt / d pT t,2 [GeV-1]
Prediction / Data
pT t,2 [GeV]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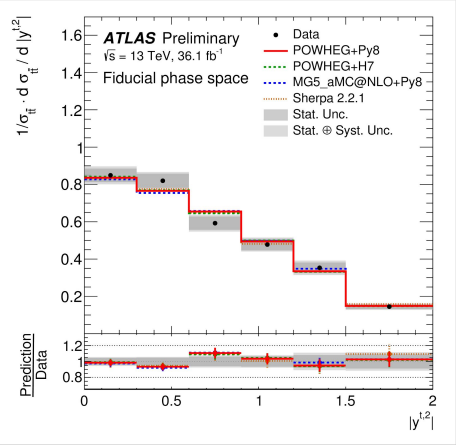
√s = 13 TeV, 36.1 fb-1
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σtt · d σtt / d |y t,1|
Prediction / Data
|y t,1|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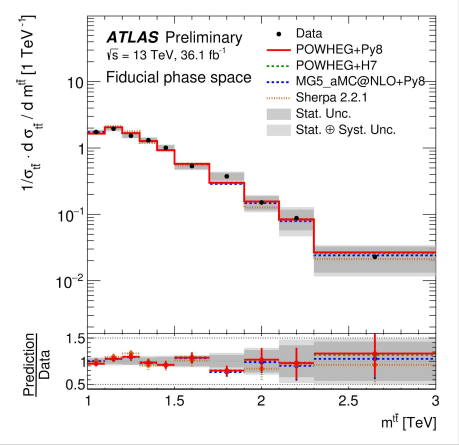
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σtt · d σtt / d |y t,2|
Prediction / Data
|y t,2|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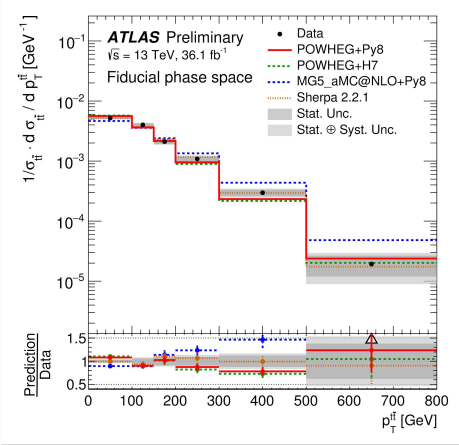
√s = 13 TeV, 36.1 fb-1
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σtt · d σtt / d mtt [1 TeV-1]
Prediction / Data
mtt [TeV]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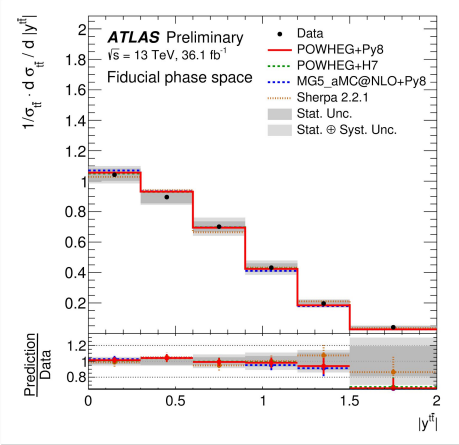
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σtt · d σtt / d pT tt [GeV-1]
Prediction / Data
pT tt [GeV]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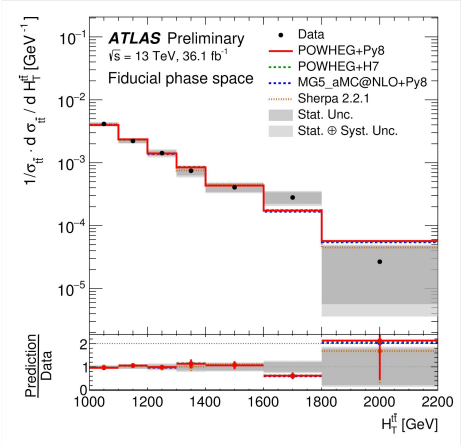
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σtt · d σtt / d |y tt|
Prediction / Data
|y tt|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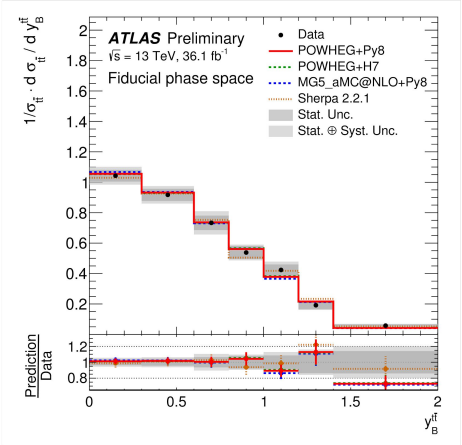
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Prediction / Data
H_T^tt̄ [GeV]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Fiducial phase space
Data
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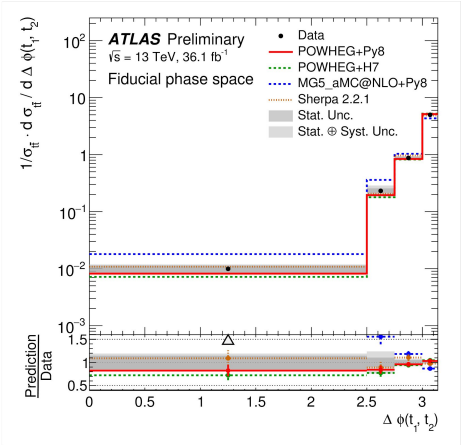
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Prediction / Data
y_B^tt̄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Fiducial phase space
Data
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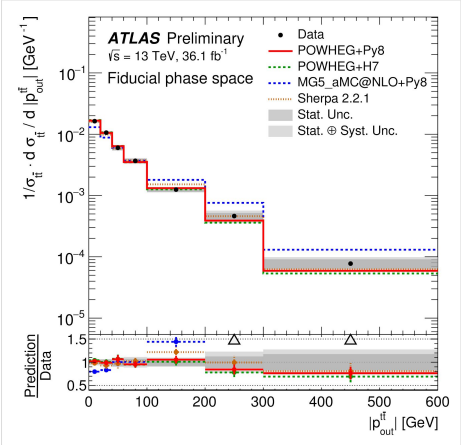
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Prediction / Data
Δ φ(t_1, t_2)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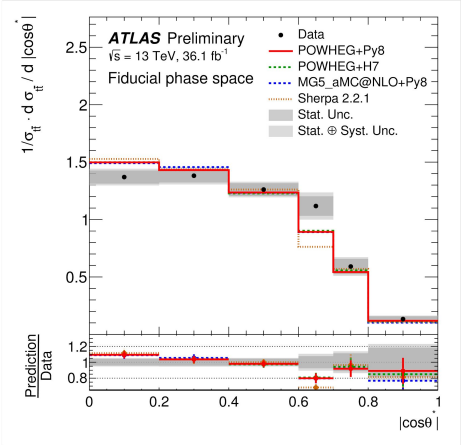
√s = 13 TeV, 36.1 fb⁻¹
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Prediction / Data
|p_out^tt̄| [GeV]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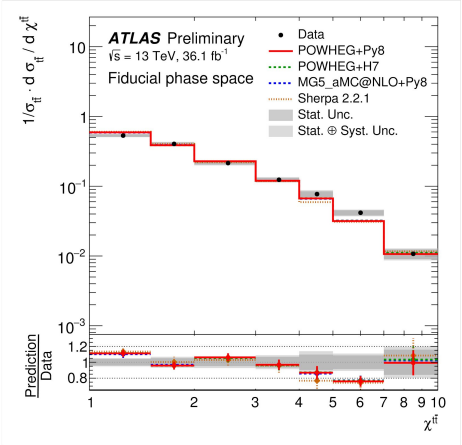
√s = 13 TeV, 36.1 fb⁻¹
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Prediction / Data
|cosθ*|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√s = 13 TeV, 36.1 fb⁻¹
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Prediction / Data
χ^tt̄

Multijet Estimate

Second-leading Large-R Jet	0t0b	1t0b	0t1b	1t1b
1t1b	J	K	L	S
0t1b	B	D	H	N
1t0b	E	F	G	M
0t0b	A	C	I	O

Leading Large-R Jet

J*O/A provides a direct estimate of region S but is sensitive to tagging correlations between the two jets.

(B/A)/(D/C) = (B*C)/(D*A) - provides an estimate of the correlation between the top tagging of the leading jet and the b-matching of the second-leading jet. It's inversion corrects for the correlation in the final estimate

$$S = \frac{J \times O}{A} \cdot \frac{D \times A}{B \times C} \cdot \frac{G \times A}{E \times I} \cdot \frac{F \times A}{E \times C} \cdot \frac{H \times A}{B \times I}$$

$$= \frac{J \times O \times H \times F \times D \times G \times A^3}{(B \times E \times C \times I)^2},$$

Similar factors correct for all b-matching and top-tagging correlations between jet 1 and jet 2

Unfolding

Uses bayesian unfolding with 4 iterations

Symbolic representation of bayesian unfolding

$$\frac{d\sigma^{\text{fid}}}{dX^i} \equiv \frac{1}{\int \mathcal{L}\, dt \cdot \Delta X^i} \cdot \frac{1}{\epsilon^i_{\text{eff}}} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\text{acc}} \cdot \left(N^j_{\text{reco}} - N^j_{\text{bg}}\right)$$

Integrated luminosity

Bin Width

Migration matrix

# of detector level events

Estimated # of background events

Unfolded differential cross-section

Efficiency correction - Accounts for events that pass the unfolded level selection but not detector level selection

Acceptance Correction - Accounts for events that pass the detector level selection but not unfolded level selection

Event display of a $t\bar{t}$ candidate event in the 2015 data. The large-R anti-k_t R=1.0 jets are shown in blue while the remaining jets are anti-k_t R=0.4 jets. The jets identified as containing b-hadrons are shown in pink. The centers of pink ellipses in the top right pad correspond to secondary vertices. The transverse momenta of the leading and second-leading large-R jets are 961 GeV and 824 GeV, respectively. The dijet invariant mass of the two large-R jets is 3.33 TeV while the τ_{32} values are 0.35 and 0.34 for the leading and second-leading large-R jets, respectively.