Differential $t\bar{t}$ cross-section measurements using boosted top quarks in the all-hadronic final state with 139/fb of ATLAS data

Division Seminar, December 1, 2022

Petr Jačka, Jiří Hejbal, Roman Lysák

Czech Academy of Sciences

Introduction

Goals

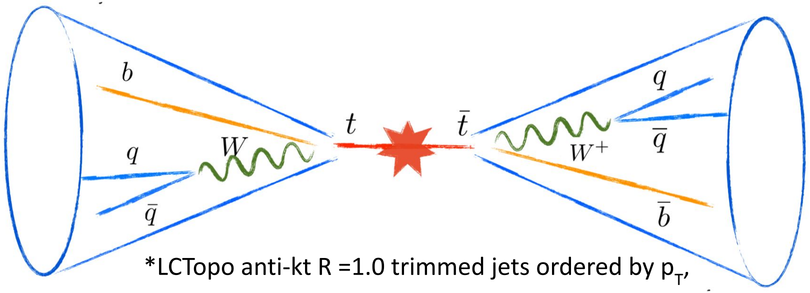
- Measurement of ttbar differential cross-sections in region with two boosted hadronic top quarks
  - 13 TeV proton-proton collisions, 139 fb^{-1}
  - 1D, 2D and 3D spectra
- Results compared to SM predictions
- EFT interpretation to study sensitivity to BSM

References

- Run II analysis: arXiv:2205.02817
  - Accepted to JHEP
- Results of the first round (2015+2016 data): 10.1103/PhysRevD.98.012003

Large-R jet* (R=1.0):

- $p_{T,J1} > 500$ GeV
- $|m_{J1}-172.5| < 50$ GeV
- $|\eta_{J1}| < 2.0$



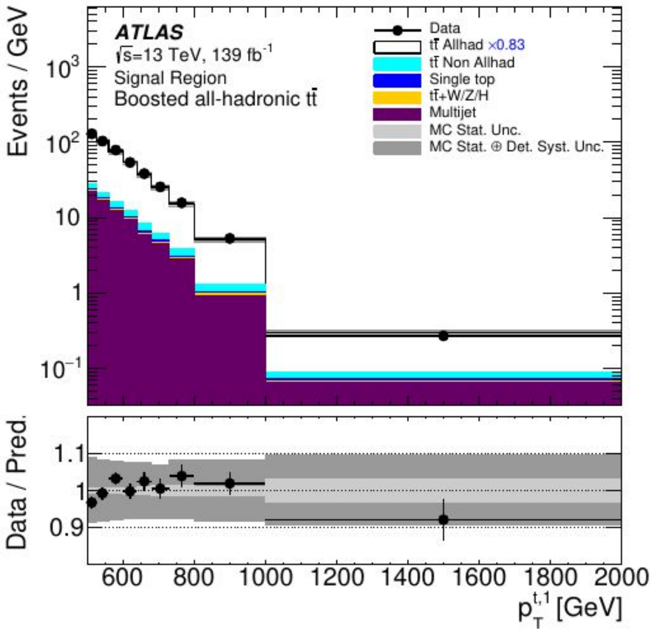
*LCTopo anti-kt R =1.0 trimmed jets ordered by p_T, selected those with mass closest to expected m_{top} = 172.5 GeV

Large-R jet* (R=1.0):

- $p_{T,J2} > 350$ GeV
- $|m_{J2}-172.5| < 50$ GeV
- $|\eta_{J2}| < 2.0$

- **Top-tagging** (DNN based on substructure) and **B-tagging** (VR track-jets, DL1r) used to reduce multijet and other background contributions

Detector level

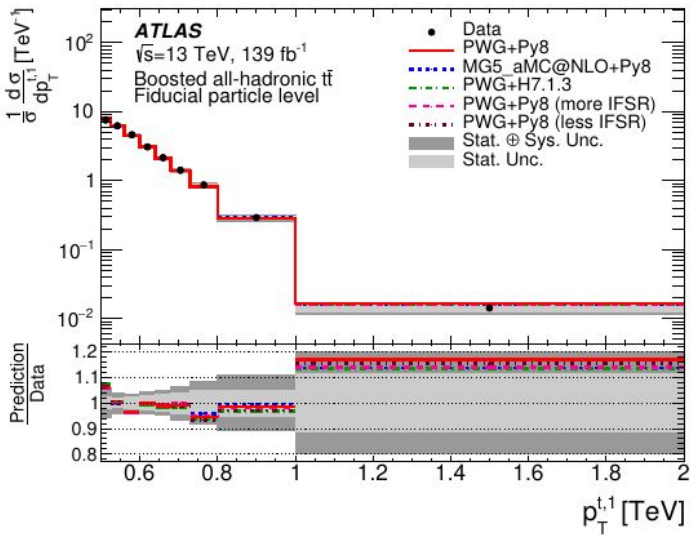


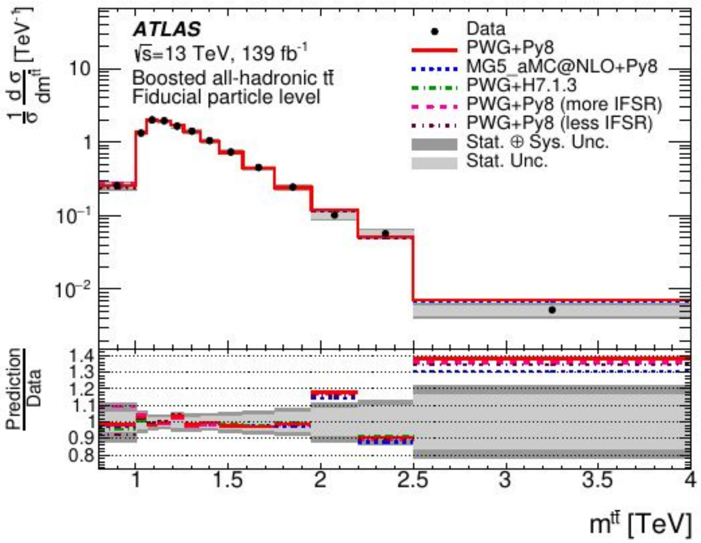
Source	Event Yields
$t\bar{t}$ (all-hadronic)	$16\,200 \pm 1400$
$t\bar{t}$ (non-all-hadronic)	625 ± 63
Single top-quarks	179 ± 21
$t\bar{t} + W/Z/H$	114 ± 11
Multijet events	2900 ± 160
All Backgrounds	3820 ± 200
Prediction	$20\,000 \pm 1600$
Data (139 fb^{-1})	$17\,261$

Detector level is formed from events recorded by the ATLAS detector

- Around 20% of background contamination
- Multijet background (dominant) determined by data-driven technique
- Other backgrounds determined using Monte Carlo samples

Particle level results

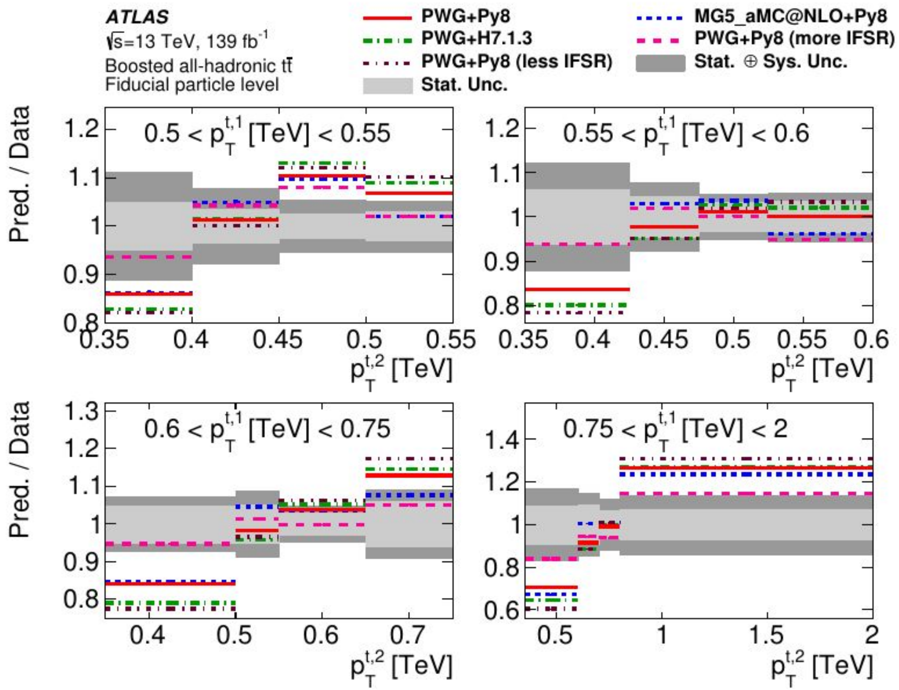




Particle level is formed from stable particles (lifetimes > 30 ps) right before they reach detector. Measured detector level spectra are corrected by unfolding procedure for comparison with SM predictions.

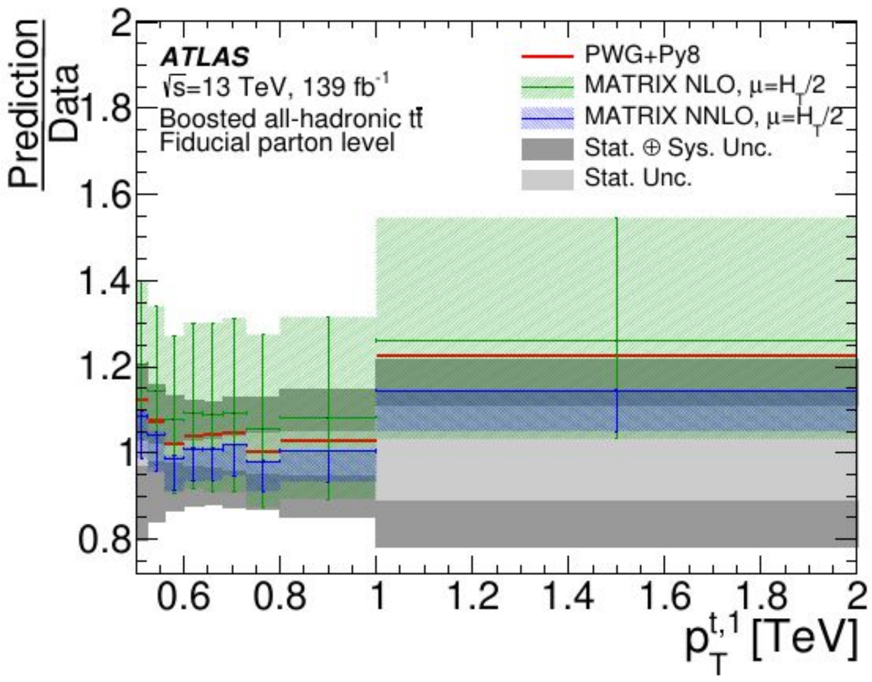
- Normalized spectra compared with NLO ME+PS predictions
- Reaching 2 TeV in top p_T and 4 TeV in ttbar mass

Particle level: 2D results: Comparison to NLO+PS generators



- Ratio plots of $p_T^{t,2}$ projections in bins of $p_T^{t,1}$
- 2D distributions provide information about correlations between variables
  - Such information can be used in MC generators tuning or to set constraints to PDF parameters
- Discrepancy in shapes is increasing with $p_T^{t,1}$

Comparison to fixed order SM NNLO



- Comparison made at the parton level
  - Made of top-antitop quarks before decay
- Asymmetric cuts applied on leading (> 500 GeV) and subleading top p_T (> 350 GeV)
- MATRIX program provides fixed order calculations up to NNLO with a possibility to define event selection and binning for 1D and/or 2D spectra

- Uncertainties of MATRIX predictions:
  - 7 point comparison → does not provide information correlations between bins →Quantitative comparison between spectra not possible

- Large instabilities are observed in finite order spectra when two tops four momenta are getting closer to each other

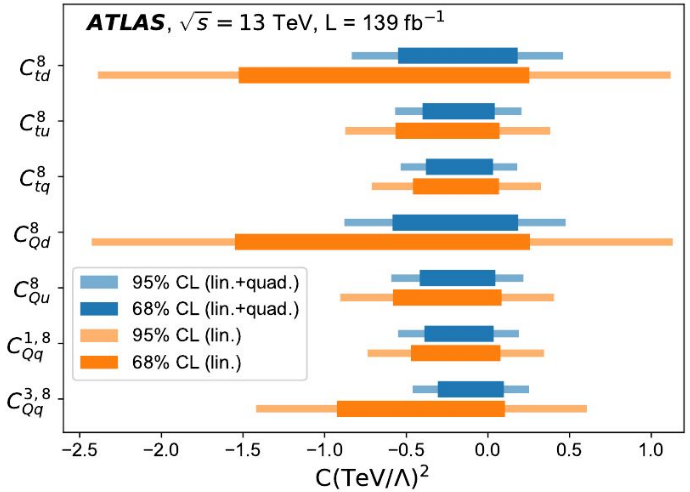
Effective field theory (EFT) interpretation

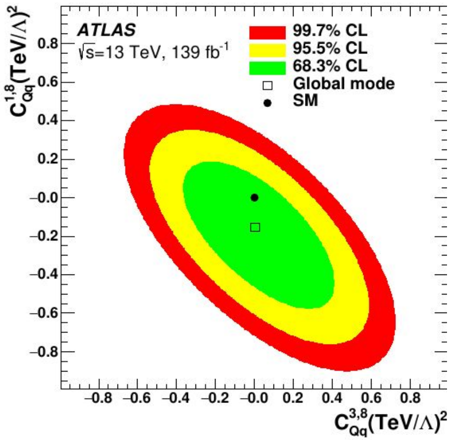
- The measured distributions are interpreted within EFT
- Using **MadGraph5_aMC@NLO** with LO EFT model (**dim6top**)
- Operators selected from Warsaw Basis
  - 2-light-quark-2-heavy-quark operators
- Using NNLO fixed order prediction as the SM prediction (σ_{SM})
- 1D and 2D limits are determined on Wilson coefficients

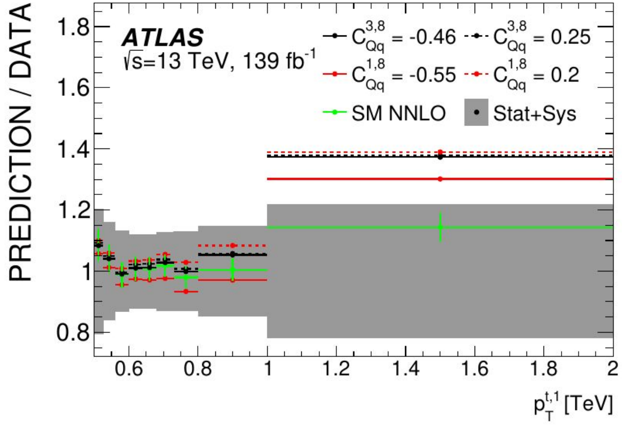
$$\sigma \sim |M|^2 = \sigma_{SM} + \frac{1}{\Lambda^2}\sigma_{SM-EFT} + \frac{1}{\Lambda^4}\sigma_{EFT-EFT}$$
$$= \sigma_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i C_i + \frac{1}{\Lambda^4}\sum_i \beta_i C_i^2$$
$$+ \frac{1}{\Lambda^4}\sum_{i,j,i\neq j} \tilde{\beta_{ij}} * C_i C_j$$

Wilson coefficients C_i give measure of strength of a given operator

parameters of EFT model: σ_{SM}, α_i, β_i, β_{ij}

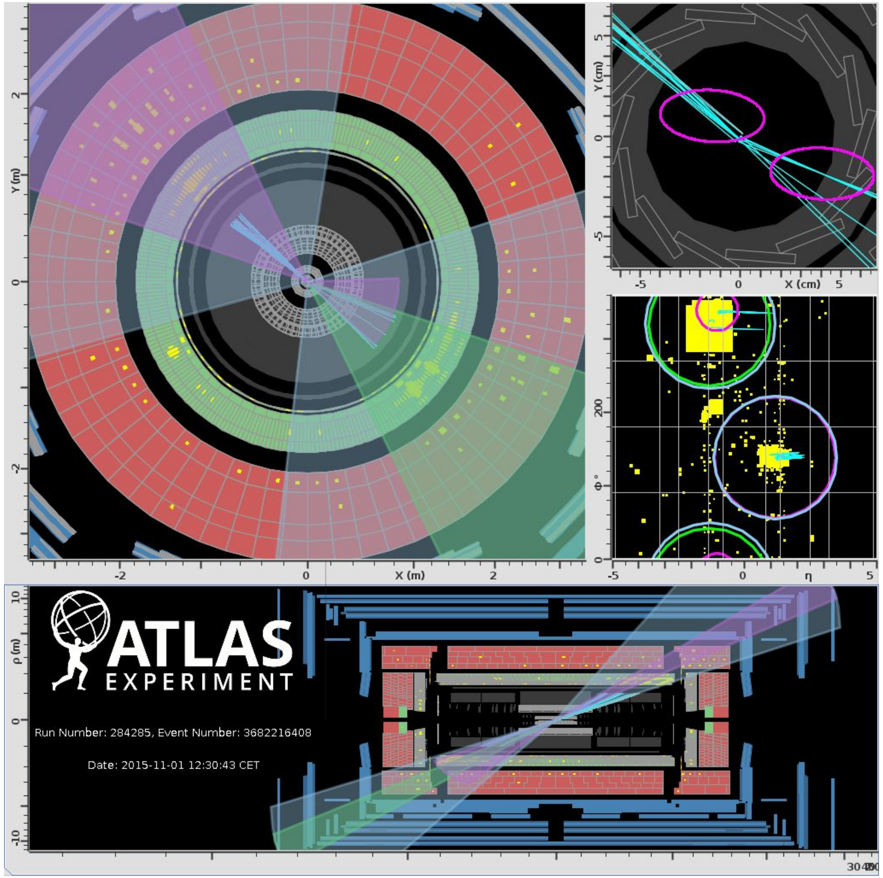






Conclusions

- First round of analysis
  - 10.1103/PhysRevD.98.012003
  - First measurement of differential cross-sections in this channel
  - Measured very highly energetic spectra
- Run II analysis:
  - arXiv:2205.02817
  - Better understanding of uncertainties, more sophisticated techniques, and more data improved significantly precision of measured spectra
  - Added 2D and 3D measurements
  - Added comparison with NNLO predictions provided by MATRIX
  - Limits set to BSM coefficients



THANK YOU FOR YOUR ATTENTION!

Backup Slides

Data sets and MC samples

- **DATA:** full Run2, Lumi = 139 fb^{-1}, inclusive high-p_T large-R jet triggers
- **MC samples:**
  - **Signal nominal sample:** Powheg + Pythia 8 (using sliced samples in H_T)
  - **Signal modelling samples:**
    - Powheg + Herwig 7.1.3 (for determination of PS+HAD uncertainties)
    - Powheg + Pythia 8 (MEC=off) (for determination of ME uncertainties)
    - MG5_aMC@NLO +Pythia 8 (for determination of ME uncertainties)
    - Powheg + Pythia 8 (hdamp=3*mtop) (for ISR/FSR uncertainty)
  - **Background samples:**
    - major background: QCD multijet ⟶ ABCD data-driven method
    - other bckg: ttbar non-allhad (Pow+Py8), tt+W/Z (MG5+Py8), ttH(Pow+Py8), single top: t-chan, Wt (Pow+Py8)
  - **EFT samples:** MG5_aMC@NLO (EFT model: dim6top) + Pythia8 (reweighting to various EFT coefficients)

Object Selection

Large-R jets

- Anti-kt LCTopo trimmed jets, R=1.0
- p_T > 200 GeV, $|\eta| < 2.0$, m > 50 GeV
- Used for top-quark reconstruction

Small-R track jets

- Variable-R track jets
- $0.02 \leq R \leq 0.4$
- p_T > 10 GeV, $|\eta| < 2.5$
- Used for b-tagging

Small-R calo jets

- Anti-kt EM P-flow, R=0.4
- p_T > 25 GeV, $|\eta| < 2.5$
- Used for control studies only

Electrons

- p_T > 25 GeV, $|\eta| < 2.5$
- ElectronID TightLH
- ElectronIsolation Gradient
- Used to veto events

Muons

- p_T > 25 GeV, $|\eta| < 2.5$
- MuonQuality Medium
- MuonIsolation FCTight_FixedRad
- Used to veto events

Background estimate

- Major background (~15%): multijets
- Other backgrounds small (<5%): MC-based

Multijet background estimation:

- Estimated by extended data-driven ABCD method
- **Apply corrections** to correlations between tagging states
- 2 parameters for each of two large-R jets (4 in total):
  - top tagging: t = 1 (yes) / 0 (no)
  - b-matching: b = 1(yes) / 0 (no)
- Events classified into 16 regions according to tagging results of two leading large-R jets
  - Signal region: S (red) [# tags = 4]
  - Validation regions: K,L,M,N (blue) [# tags = 3]
  - 11 multijet background enriched regions: [# tags <=2]

- Estimation in the signal region:

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

2nd large-R jet				
1t1b	J (7.0%)	K (25%)	L (39%)	S
0t1b	B (1.2%)	D (5.0%)	H (9.0%)	N (47%)
1t0b	E (0.5%)	F (2.3%)	G (4.9%)	M (31%)
0t0b	A (0.09%)	C (0.5%)	I (1.1%)	O (9.0%)
	0t0b	1t0b	0t1b	1t1b
	Leading large-R jet			

In parentheses: (MC signal)/Data ratios

Signal region yields

Source	Event Yields
$t\bar{t}$ (all-hadronic)	$16\,200 \pm 1400$
$t\bar{t}$ (non-all-hadronic)	625 ± 63
Single top-quarks	179 ± 21
$t\bar{t} + W/Z/H$	114 ± 11
Multijet events	2900 ± 160
All Backgrounds	3820 ± 200
Prediction	$20\,000 \pm 1600$
Data ($139\ \text{fb}^{-1}$)	$17\,261$

- Signal / Background ~ 4
- Prediction / data ~ 1.16
- Uncertainties cover limited statistics in data & MC, and all detector systematics

Unfolding and phase space definitions

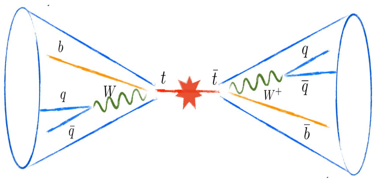
- Use iterative Bayesian unfolding algorithm (N_{iter} =4)
- The unfolded differential cross-section is schematically given by:

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

Particle level fiducial phase space definition:

Truth trimmed jets R=1.0

$p_{T,J1}$ > 500 GeV
$|m_{J1}-m_{Top}|$ < 50 GeV
$|\eta_{J1}|$< 2

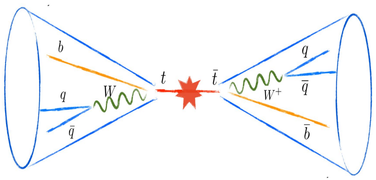


$p_{T,J2}$ > 350 GeV
$|m_{J2}-m_{Top}|$ < 50 GeV
$|\eta_{J2}|$< 2

- Both jets matched with B-hadron
- Top tagging not applied

Parton level limited phase space definition:

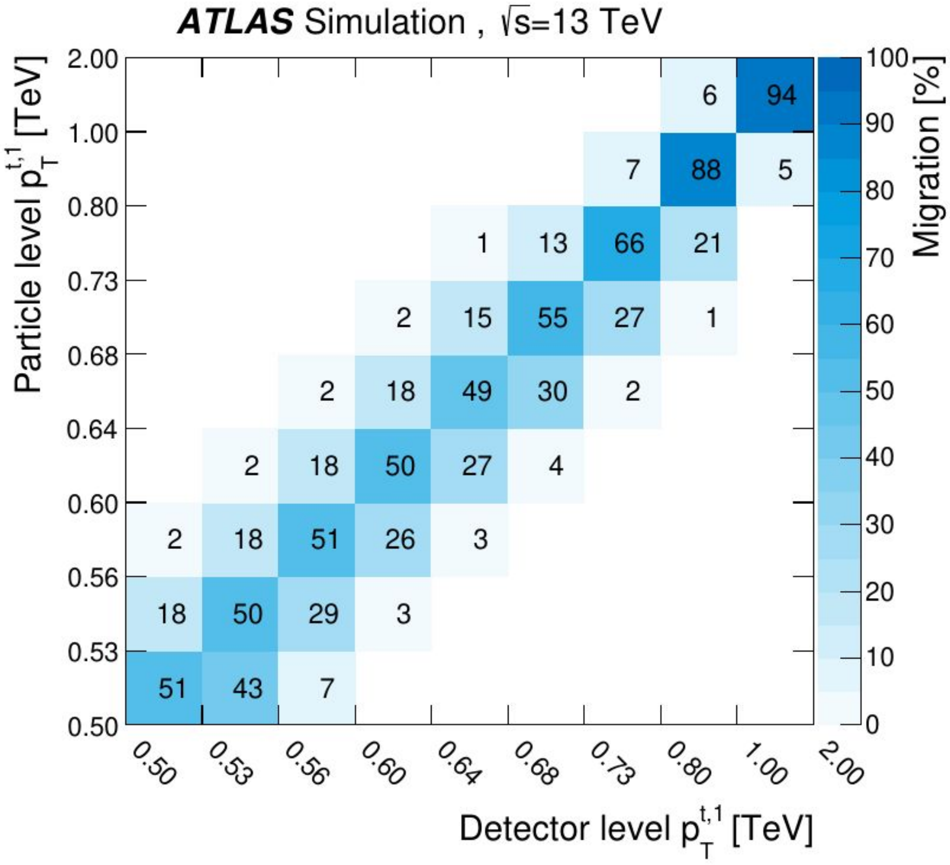
$p_{T,top1}$ > 500 GeV

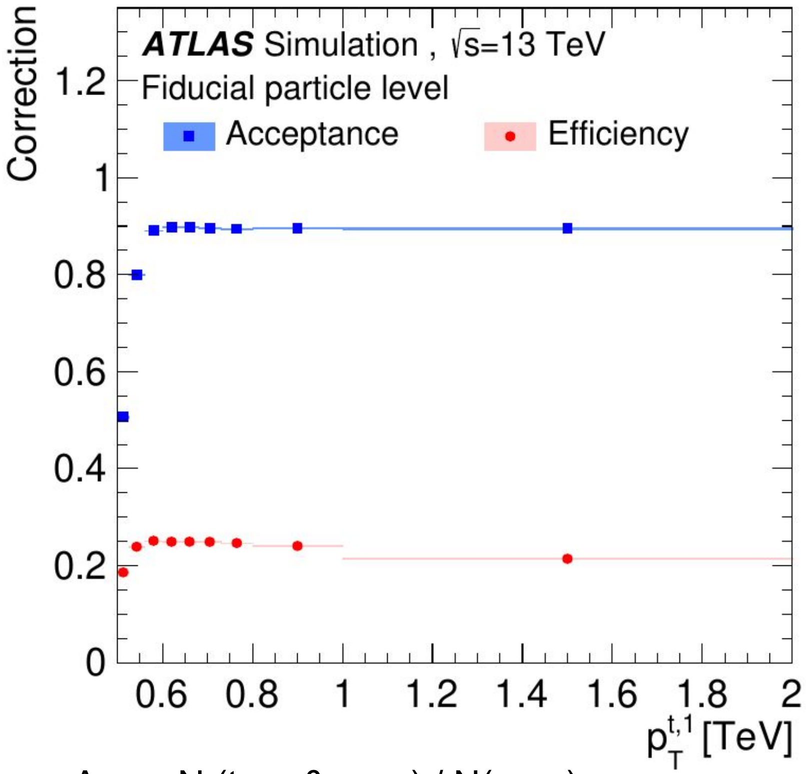


$p_{T,top2}$ > 350 GeV

- Last top quark in MC chain (after radiation)

Unfolding ingredients





Acc = N (true & reco) / N(reco)

Eff = N (true & reco) / N(true)

Summary of systematic uncertainties

Detector Systematic uncertainties:

- luminosity: 1.7% - using recommended GRLs for physics analyses
- pileup: internal reweighting
- Large-R jets: JES/JER/JMS/JMR based on the consolidated recommendations
- Top-tagging: scale-factors based on the consolidated recommendations
- B-tagging: scale-factors variation using **customized CDI file**: Improving extrapolation uncertainties

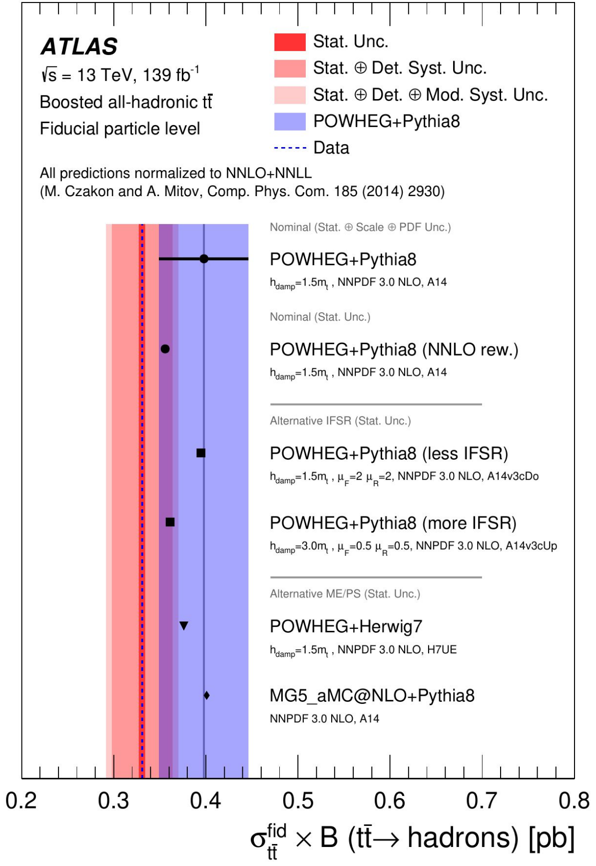
Signal modeling uncertainties:

- ISR: ⟶ changing independently hdamp(=3*m_{top}), μ_R, μ_F , Var3C tune parameter
- FSR: ⟶ changing FSR scale: μ_R (FSR)
- PDF ⟶ reweighting according to PDF4LHC prescription
- PS and hadronization ⟶ Powheg + Herwig7 vs nominal
- Hard scattering modeling ⟶ MG5_aMC@NLO+Py8 vs Pow+Py8 (MEC=off)

Background modeling uncertainties:

- Uncertainties in cross-sections of all MC background samples: ttbar nonallhadronic, Wt-single top, single top t-channel, ttX(X=HWZ)
- Additional 50% uncertainty in normalization added to Wt-single top sample to cover ambiguity in Wt-single top channel definition

Inclusive cross section measurement at particle level



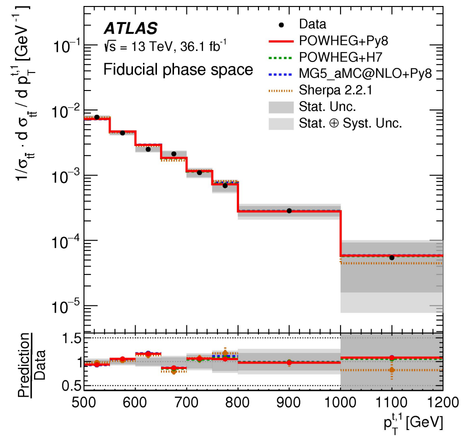
Measured cross section:

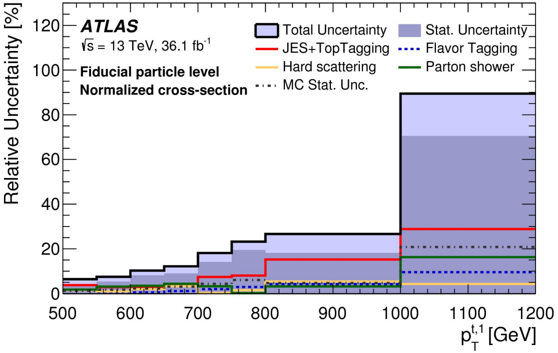
$$\sigma_{fid} = 330 \pm 3.0(stat) \pm 38(syst)\ \text{fb}$$

Source	Relative Uncertainty [%]
Top-tagging	7.8
JES ⊕ JER	4.2
JMS ⊕ JMR	1.1
Flavour tagging	2.9
Alternative hard-scattering model	0.9
Alternative parton-shower model	4.3
ISR/FSR + scale	4.9
PDF	0.8
Luminosity	1.7
MC sample statistics	0.4
Total systematic uncertainty	11.8
Statistical uncertainty	1.0
Total uncertainty	11.8

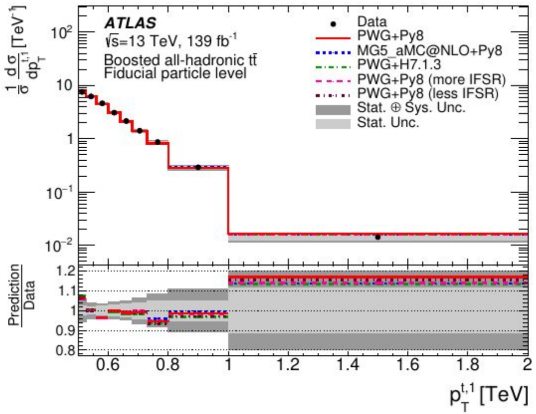
Unfolding results: Comparison to previous results

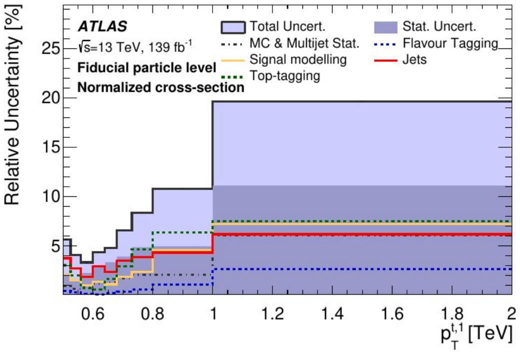
Old results





New results





- Achieved significant improvement in precision of the measurement
- Level of agreement between data & predictions is similar