Measurements of $t\bar{t}$ production cross sections with the ATLAS experiment at the LHC

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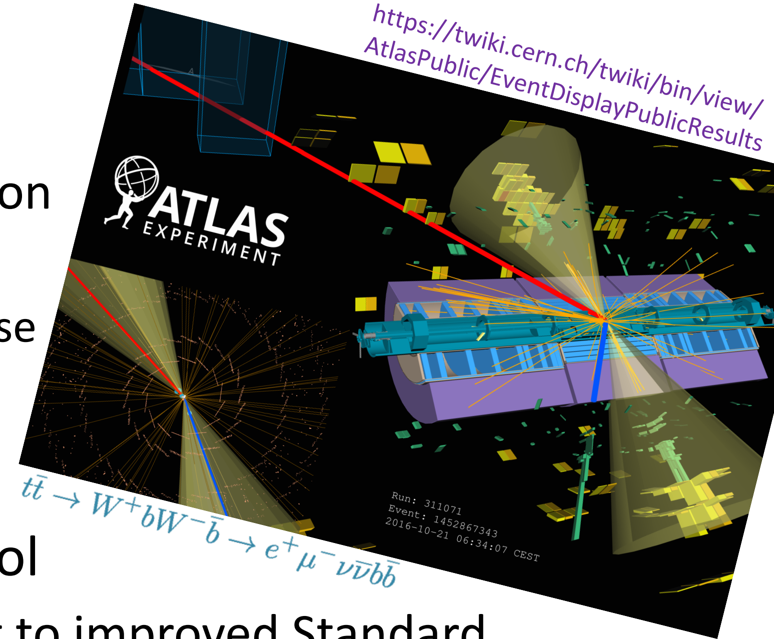
Probing the Standard Model with $t\bar{t}$ production



- LHC as a top-quark factory
  - Large statistics allows percent-level precision in cross section measurements
    - Multiple complementary channels and phase space regions

- Precise $t\bar{t}$ measurements, a powerful tool
  - Probing QCD at high energy scales, leading to improved Standard Model simulation
  - Extracting fundamental parameters, such as the top mass
  - $t\bar{t}$ kinematics potentially very sensitive to Beyond the Standard Model effects
  - $t\bar{t}$ (+jets) is a major background to many important signals
    - both Standard Model measurements and beyond the Standard Model searches

Differential cross sections

- ATLAS has extensively studied $t\bar{t}$ production:
  - differential and double differential cross section measurements

- Normalised differential cross section further reduces systematic uncertainties
  - Most of the presented analysis focus on normalised results
    - Complemented by inclusive cross section measurements

- Very large sets of variables have been studied
  - All also provide numerical comparison with simulation, by computing χ^2

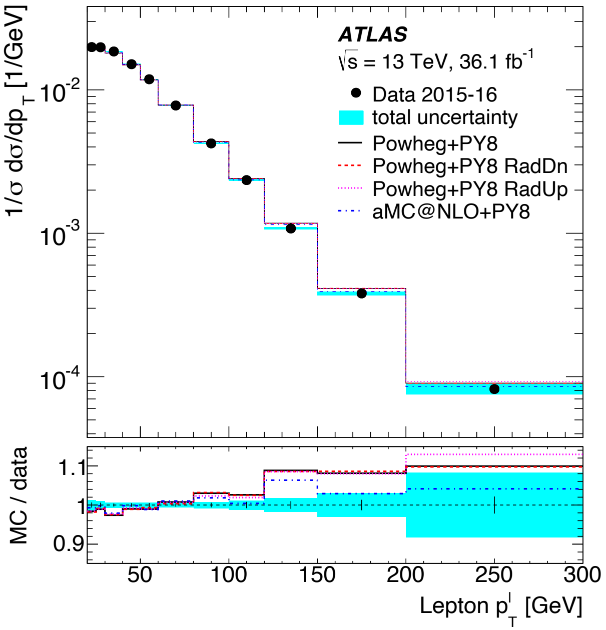
$\mathcal{L} = 36.1\ \text{fb}^{-1}$

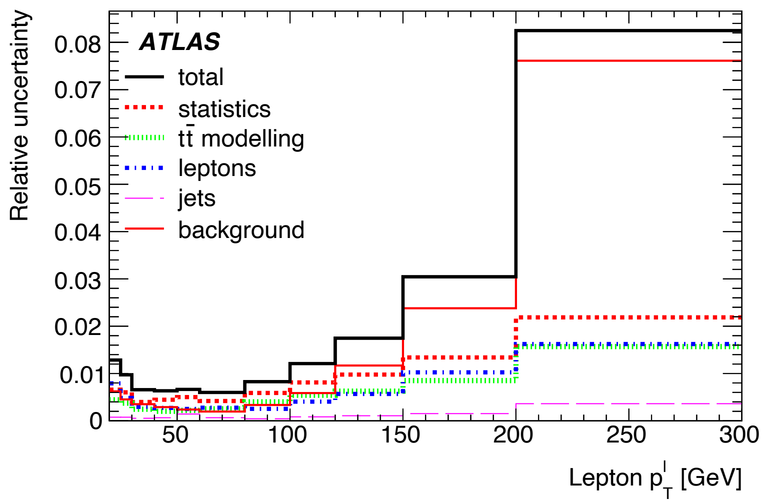
Eur. Phys. J. C 80 (2020) 528

Differential cross section: di-lepton

$t\bar{t} \to W^+bW^-\bar{b} \to e^+\mu^-\nu\bar{\nu}b\bar{b}$

- Performed in $e\mu$ channel
  - ➤Least affected by background
  - Opposite sign $e\mu$ pair + 1 or 2 b-Tagged jets
- (Double) differential cross sections as a function of lepton kinematic
  - no attempt to reconstruct $t\bar{t}$
  - Cross section extracted in every bin, by interpolating the number of events with 1 and 2 b-jets
    - ➤Method reduces dependence on JES and b-tagging uncertainty
- Dominant systematic uncertainties: MonteCarlo modelling (signal and background), lepton reconstruction





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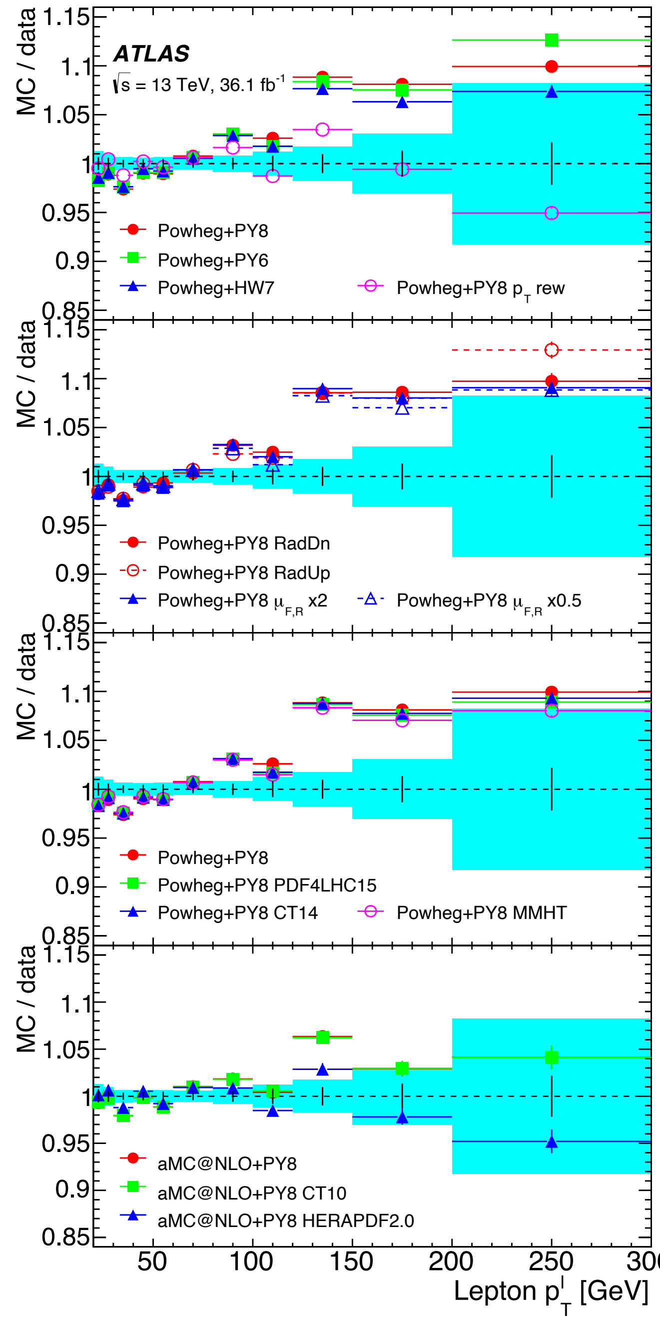
Eur. Phys. J. C 80 (2020) 528

Differential cross section: di-lepton

- Detailed comparison with multiple NLO + Parton Shower simulations
- Results compared to multiple theoretical predictions
  - Matrix Element generators
  - Parton Showers
  - Varied generator parameters, e.g:
    - factorisation/renormalisation scales,
    - amount of Parton Shower radiation
  - PDF sets
- Overall good agreement
- Poor agreement observed in some kinematic regions, such as
  - high lepton p_T (Powheg, see figure)
  - low dilepton mass (all simulations)



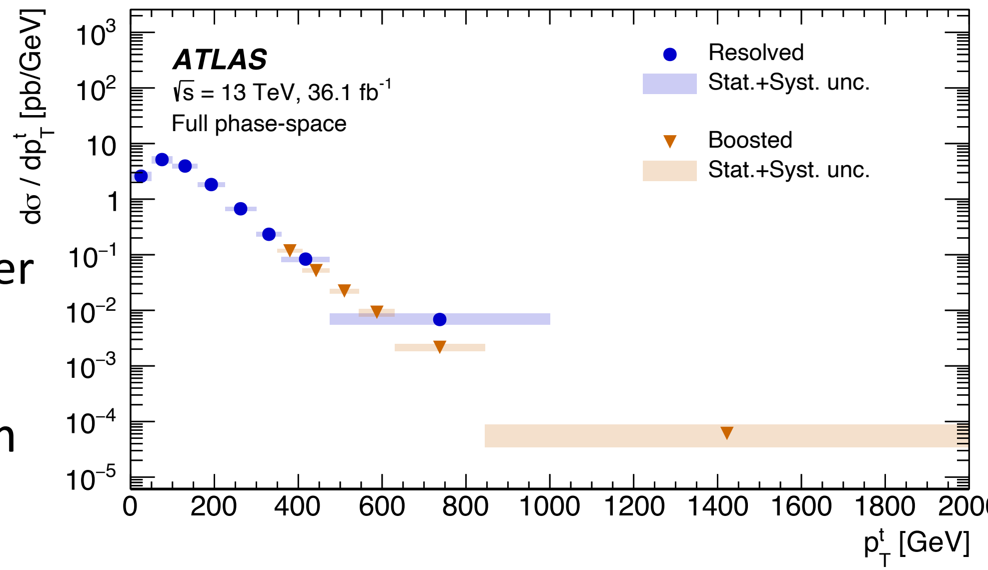
$\mathcal{L} = 36.1\ \text{fb}^{-1}$

[Eur. Phys. J. C 80 (2020) 1092]

$t\bar{t} \to W^+ b W^- \bar{b} \to \ell\nu + \text{jets}$

Differential cross section: ℓ+jets

- Two topologies are considered
  - *Resolved*: hadronic *t* decay reconstructed as 3 distinct jets
  - *Boosted*: hadronic *t* decay reconstructed as a single jet of larger radius
- *t* four-momenta reconstructed from selected jets, leptons and missing transverse momentum



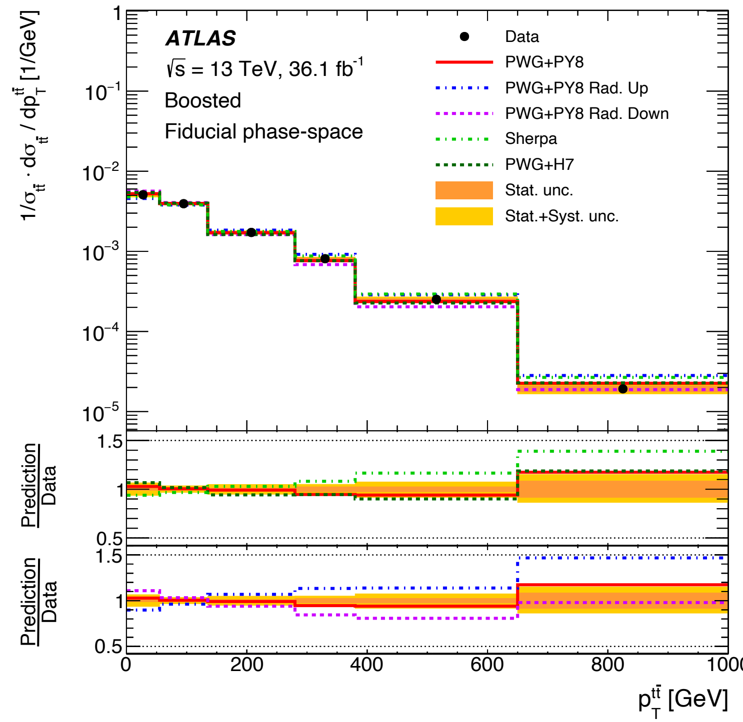
- Large set of variables, both differential and double differential cross sections
  - modelling of initial/final-state radiation also explored
- Data unfolded to both fiducial and total phase space
  - ➢boosted limited to the region of high top-quark transverse momentum
- Systematic uncertainties dominated by Jet Energy Scale (resolved) and signal modelling (boosted)

$\mathcal{L} = 36.1\ \mathrm{fb}^{-1}$

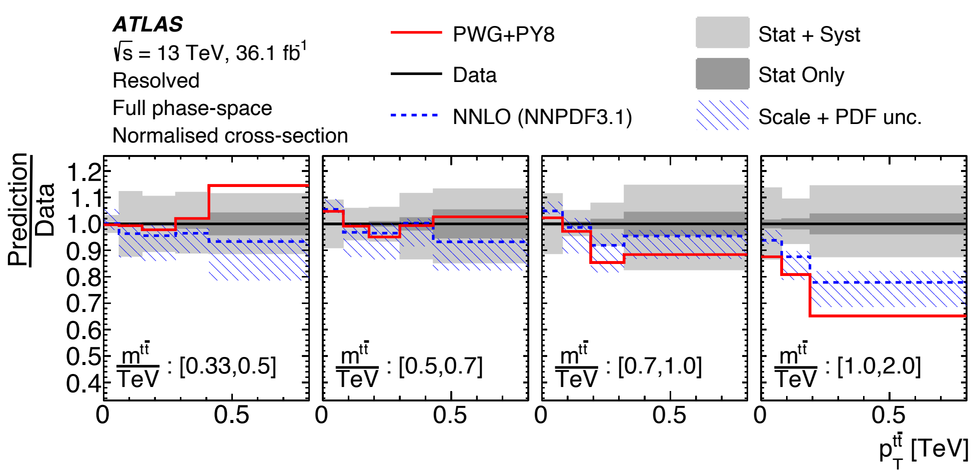
Eur. Phys. J. C 80 (2020) 1092

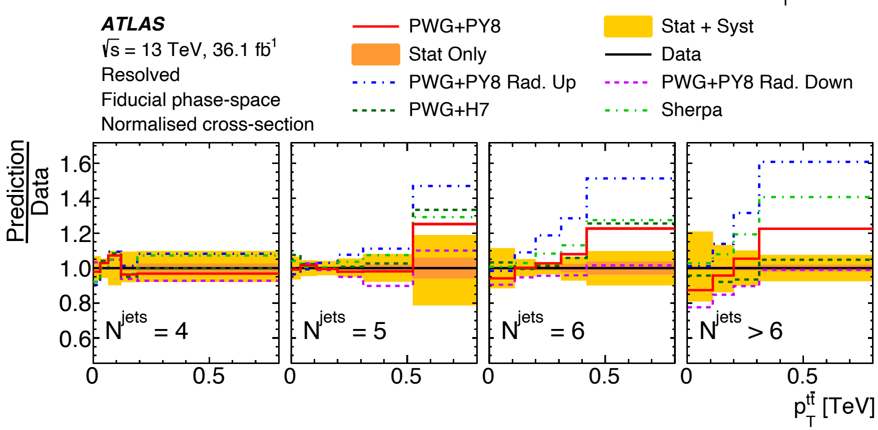
Differential cross section: ℓ+jets

- Fiducial cross section
  - Multiple generators tested, mostly in good agreement with data
    - Best results: Powheg+Pythia8/Herwig7
  - Poor agreement in specific phase space regions
    - Predicted p_T spectrum tends to be too hard



- Cross section in full phase space
  - Comparison between NLO + Parton Shower and NNLO calculation
  - NNLO gives mostly better agreement
    - except for double differential cross section in $m^{t\bar{t}}$ and p_T^t





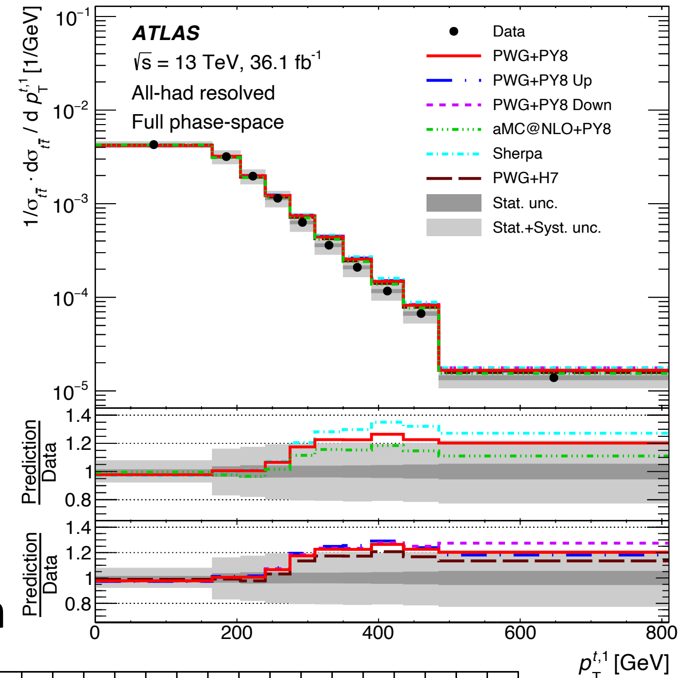
$\mathcal{L} = 36.1\ \text{fb}^{-1}$

JHEP 01 (2021) 033

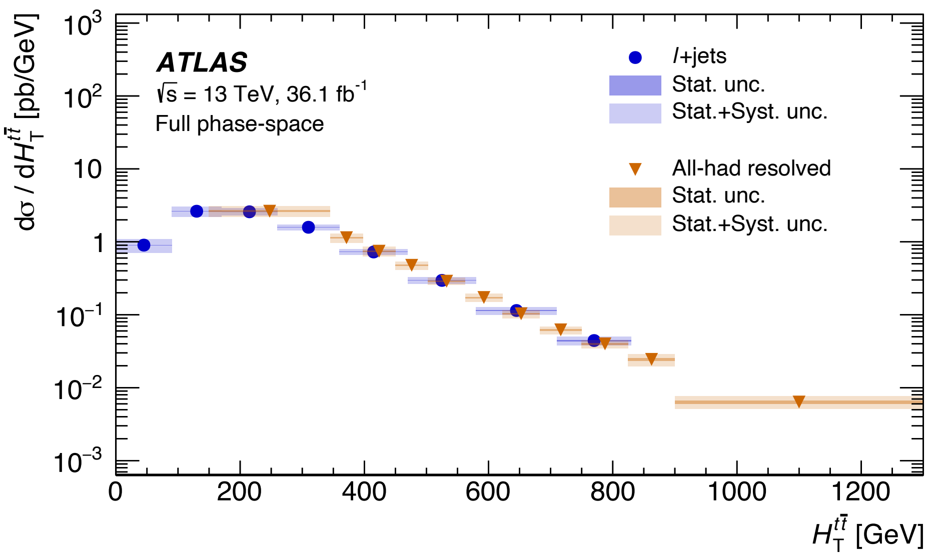
$t\bar{t} \to W^+bW^-\bar{b} \to \text{jets}$

Differential cross section: all-hadronic

- Latest result (2021) in the resolved channel
  - 6 resolved jets and no leptons
- $t\bar{t}$ fully reconstructed
  - ➤No direct neutrinos from $W \to \ell\nu$
  - Improved resolution with respects to ℓ+jets
    - ➤counter-balances the large multi-jet background
- Largest systematics from signal modelling and uncertainties in multi-jet background estimation



- Cross sections measured in both fiducial and total phase space
  - Total cross section in agreement with ℓ+jets channel



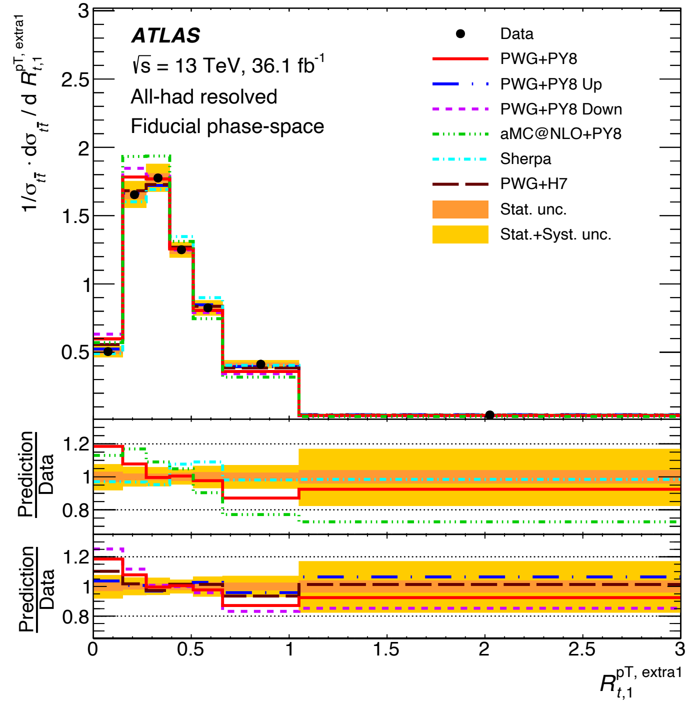
JHEP 01 (2021) 033

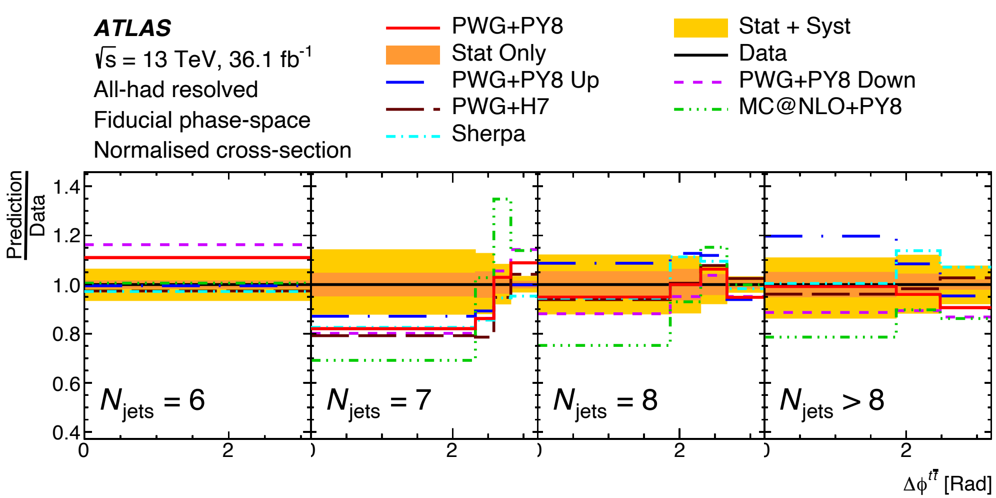
$\mathcal{L} = 36.1\ \mathrm{fb}^{-1}$

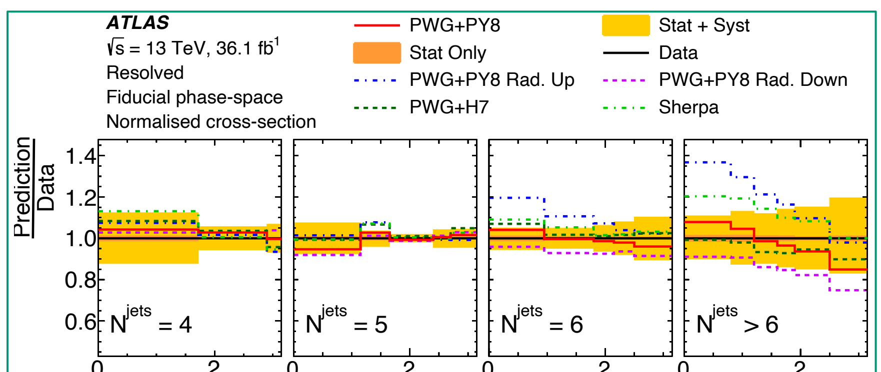
Differential cross section: all-hadronic

- Similar set of $t\bar{t}$ kinematic variables as in ℓ+jets
  - Results are in agreement with ℓ+jets for some variables (e.g. $t\bar{t}$ p_T)
  - Other variables exhibit different behaviour in the two channels

- Effect of additional jet radiation also extensively studied
  - Multiple p_T ratios between top-quark and additional jets







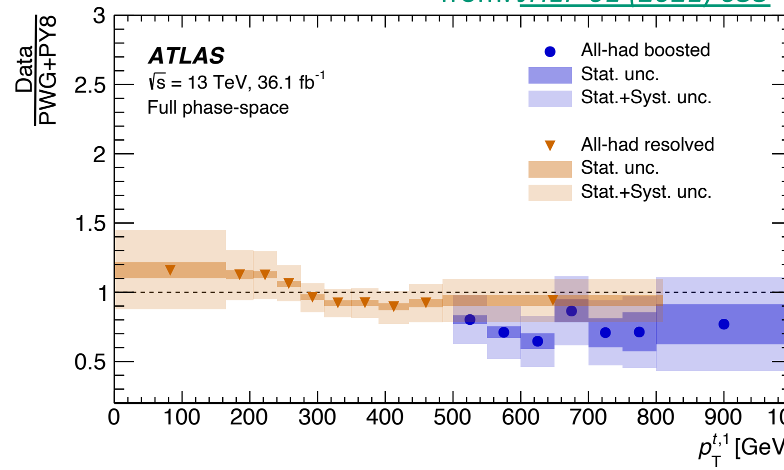
ℓ+jets, from Eur. Phys. J. C 80 (2020) 1092

$\mathcal{L} = 36.1\ \text{fb}^{-1}$

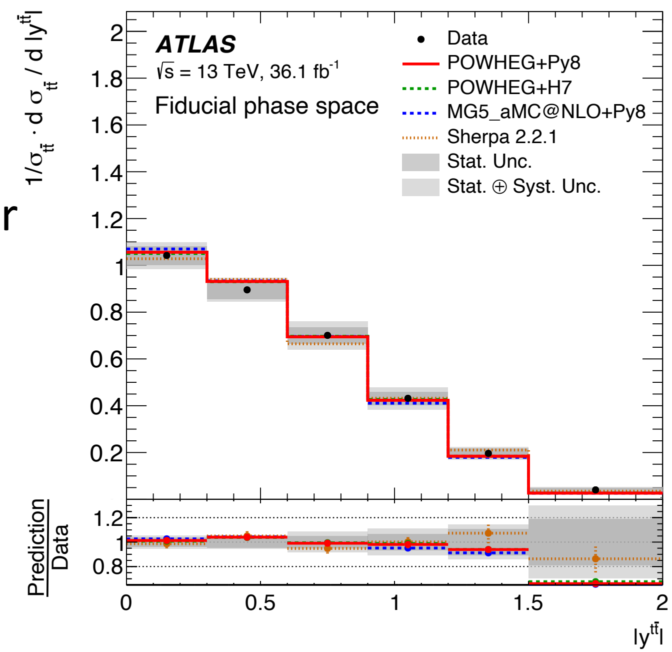
Phys. Rev. D 98 (2018) 012003

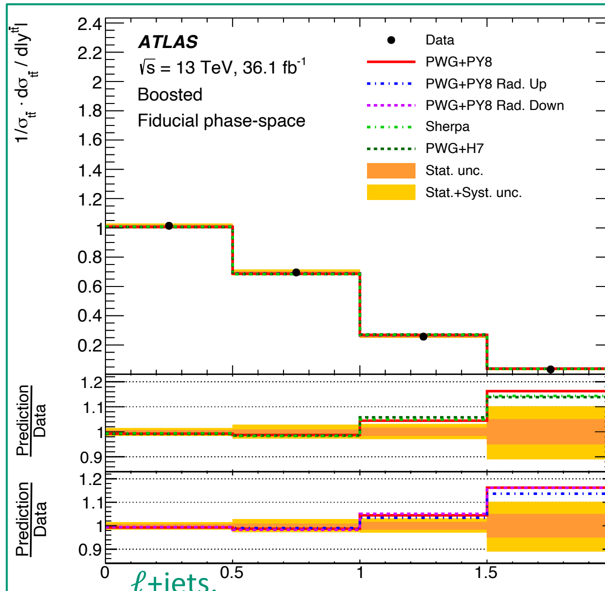
Differential cross section: all-hadronic, boosted

from: JHEP 01 (2021) 033



- All-hadronic topology initially tested in boosted channel (2018)
  - two jets of large radius and high p_T
- Consistent results with resolved channel analysis
  - from comparison with Powheg+Pythia8
- Generally well modelled
  - uncertainties tend to be larger than for ℓ+jets boosted analysis
  - poorer modelling still visible in some kinematic regions





ℓ+jets, from Eur. Phys. J. C 80 (2020) 1092

Inclusive cross section

- The inclusive cross section is also measured
  - To complement the set of normalised differential cross sections

- Most of the presented analyses: inclusive cross section extracted in the same way as differential cross section
  - Except that all events are grouped into a single bin
  - No inclusive cross section fit (profile Likelihood) has been applied

- Except for the ℓ+jets channel, for which a dedicated inclusive cross section measurement is available
  - full Run2 statistics (139 fb^{-1}, 2020)

$\mathcal{L} = 36.1\ \text{fb}^{-1}$

JHEP 01 (2021) 033 (resolved)
Phys. Rev. D 98 (2018) 012003 (boosted)

Inclusive cross section: all hadronic

- Inclusive cross section part of both resolved and boosted all-hadronic papers

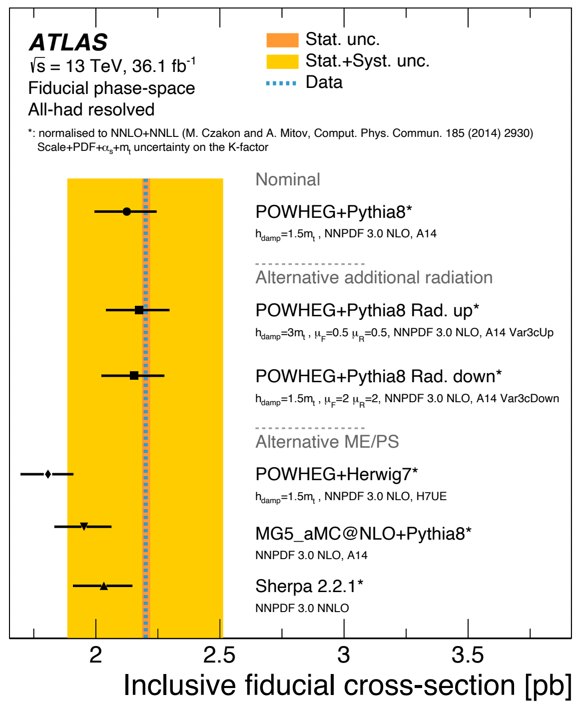
- Cross section in fiducial phase space:
  - Limited discrimination between generator parameters due to large uncertainty
  - Boosted cross section overestimated by most simulations

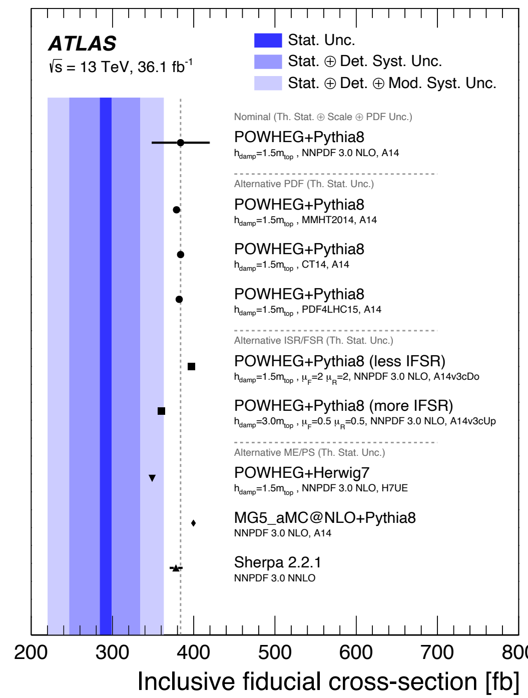
- Resolved channel also provides total cross section measurements

$$\sigma_{t\bar{t}} = 864 \pm 127\ (\text{stat.}\ + \text{syst.})\ \text{pb}$$

NNLO+NNLL prediction:

$$\sigma_{t\bar{t}} = 832^{+20}_{-29}(\text{scale}) \pm 35\ (\text{PDF},\alpha_S)\ \text{pb}$$





$\mathcal{L} = 139\ \text{fb}^{-1}$

Inclusive cross section: ℓ+jets

Phys. Lett. B 810 (2020) 135797

- Dedicated analysis measuring inclusive cross section in both total and fiducial phase space
- Simultaneous profile Likelihood fit in 3 signal regions:
  - they differ by the cuts on b-tagged jets and jet multiplicity
  - different sensitivities to modelling of b-jets and extra radiation
- Largest uncertainty from modelling of signal showering and hadronisation
  - large contribution from luminosity uncertainty

Category	$\frac{\Delta\sigma_{\text{fid}}}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta\sigma_{\text{inc}}}{\sigma_{\text{inc}}}$ [%]
Signal modelling		
$t\bar{t}$ shower/hadronisation	±2.8	±2.9
$t\bar{t}$ scale variations	±1.4	±2.0
Top p_T NNLO reweighting	±0.4	±1.1
$t\bar{t}$ h_{damp}	±1.5	±1.4
$t\bar{t}$ PDF	±1.4	±1.5
Background modelling		
MC background modelling	±1.8	±2.0
Multijet background	±0.8	±0.6
Detector modelling		
Jet reconstruction	±2.5	±2.6
Luminosity	±1.7	±1.7
Flavour tagging	±1.2	±1.3
E_T^{miss} + pile-up	±0.3	±0.3
Muon reconstruction	±0.6	±0.5
Electron reconstruction	±0.7	±0.6
Simulation stat. uncertainty	±0.6	±0.7
Total systematic uncertainty	±4.3	±4.6
Data statistical uncertainty	±0.05	±0.05
Total uncertainty	±4.3	±4.6

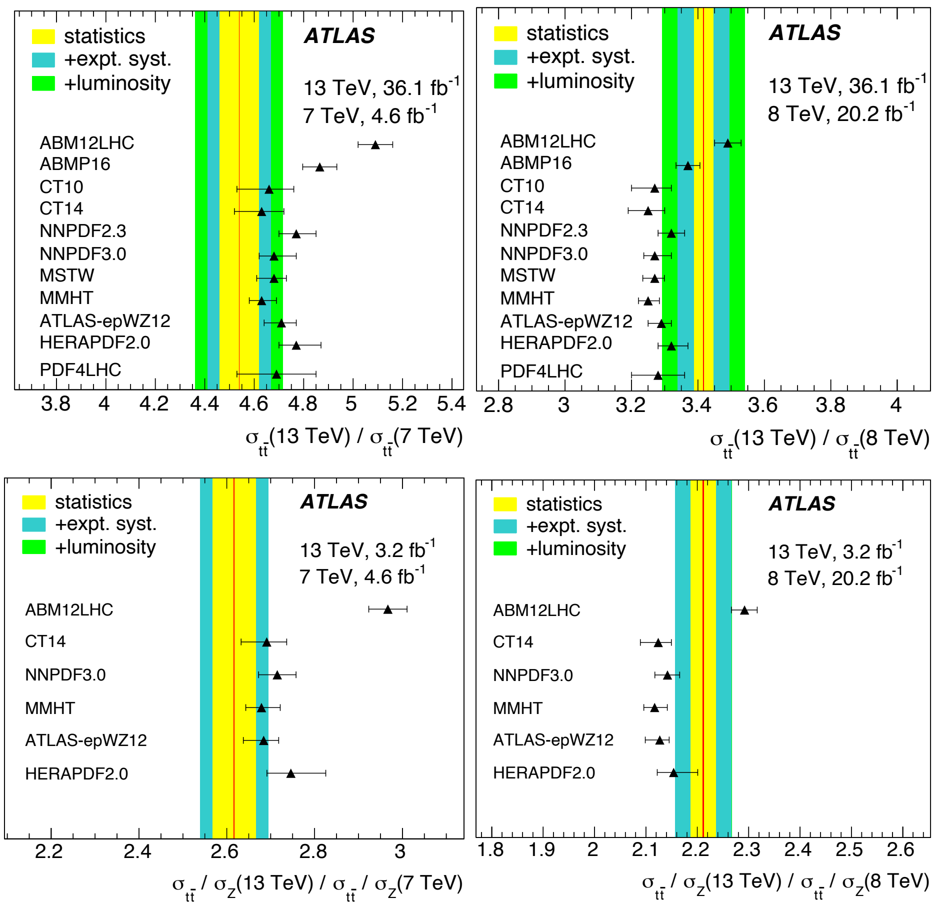
		Relative unc.
$\sigma_{t\bar{t}} = 830 \pm 0.4\ (\text{stat.}) \pm 36\ (\text{syst.}) \pm 14\ (\text{lumi.})\ \text{pb}$	ℓ+jets this measurement	4.6%
$\sigma_{t\bar{t}} = 826.4 \pm 3.6\ (\text{stat}) \pm 11.5\ (\text{syst}) \pm 15.7\ (\text{lumi}) \pm 1.9\ (\text{beam})\ \text{pb}$	di-lepton [Eur. Phys. J. C 80 (2020) 528]	2.4%
$\sigma_{t\bar{t}} = 864 \pm 127\ (\text{stat.} + \text{syst.})\ \text{pb}$	all-had. [JHEP 01 (2021) 03]	15%
$\sigma_{t\bar{t}} = 832^{+20}_{-29}\ (\text{scale}) \pm 35\ (\text{PDF},\alpha_S)\ \text{pb}$	NNLO+NNLL (Top++2.0)	

$\mathcal{L} = 36.1\ \text{fb}^{-1}$

Eur. Phys. J. C 80 (2020) 528

Inclusive cross section: di-lepton

- Total and fiddle inclusive cross section
  - part of the $e\mu$ channel paper
- Systematics further reduced by computing cross section ratio
  - to 7 and 8 TeV measurements
  - and to Z production cross section
  - Some discrimination between different PDF sets
- Inclusive cross section dependence on top-quark pole mass exploited to derive indirect measurement



$$m_t^{\text{pole}} = 173.1^{+2.0}_{-2.1}\ \text{GeV}$$ [ATLAS di-leptonic $t\bar{t}$, this measurement]

$$m_t^{\text{pole}} = 173.1 \pm 0.9\ \text{GeV}$$ [Particle Data Group, *Phys. Rev. D 98 (2018) 030001*]

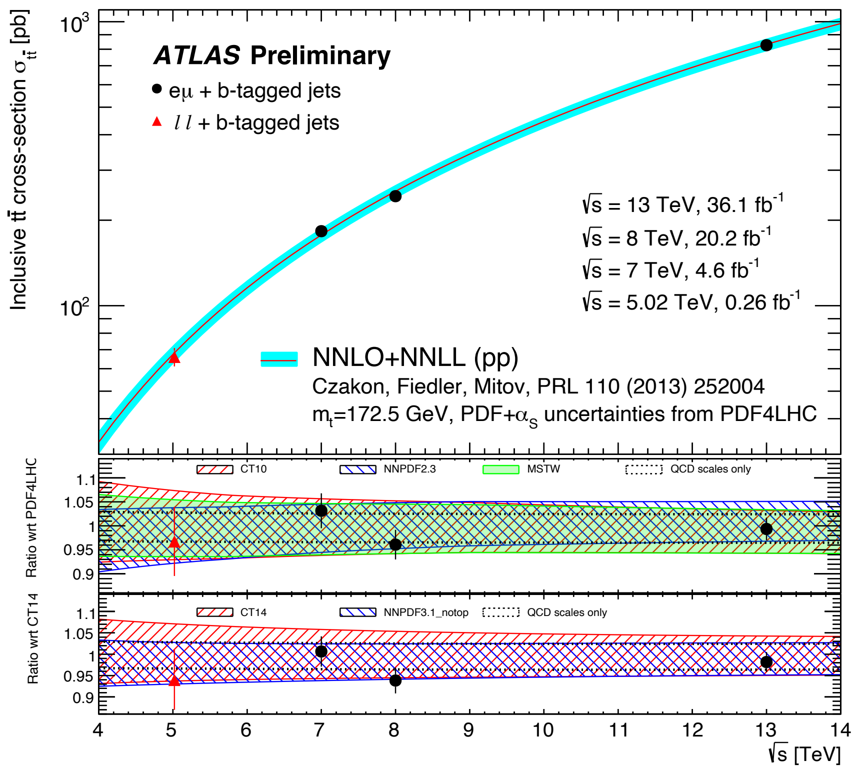
$\mathcal{L} = 257\ \mathrm{pb}^{-1}$

ATLAS-CONF-2021-003

$t\bar{t} \to W^+ b W^- \bar{b} \to (e^+\mu^-/e^+e^-/\mu^+\mu^-)\nu\bar{\nu}b\bar{b}$

Inclusive cross section: di-lepton at 5 TeV

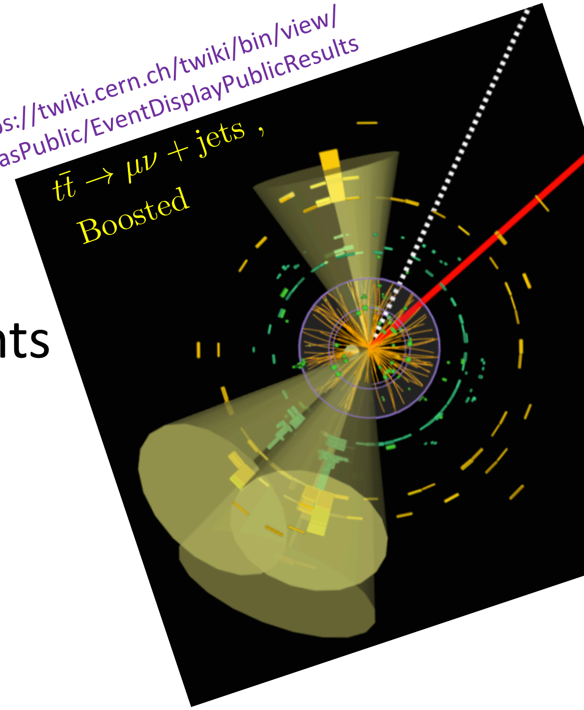
- Very recent di-lepton analysis using 257 pb^{-1} at 5.02 TeV
  - To improve the statistics, analysis also includes opposite sign *ee* or $\mu\mu$
  - Cross section extraction similar to the 13 TeV di-lepton analysis
- Consistent results between different centre-of-mass energies
  - some discrimination between PDF sets



Uncertainty	σ (%)
Data statistics	6.8
generator	1.2
hadronisation	0.2
Initial/final state radiation	1.0
heavy-flavour production	0.2
Parton distribution functions	0.3
Electron energy scale	0.1
Electron energy resolution	0.1
Electron identification	0.6
Electron charge misidentification	0.0
Electron isolation	0.5
Muon momentum scale	0.1
Muon momentum resolution	0.0
Muon identification	0.3
Muon isolation	0.6
Lepton trigger	0.2
Jet energy scale	0.1
Jet energy scale extrapolation	0.0
Jet energy resolution	0.1
Pileup jet veto	0.0
b-tagging efficiency	0.1
b-tag mistagging	0.1
E_T^{miss} soft particle modelling	0.1
Single-top cross-section	1.0
Single-top/ interference	0.2
Single-top modelling	0.4
Z+jets extrapolation	0.7
Diboson cross-sections	0.3
Misidentified leptons	0.7
Simulation statistics	0.2
Integrated luminosity	1.8
Beam energy	0.3
Total uncertainty	7.5

Conclusions

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayPublicResults



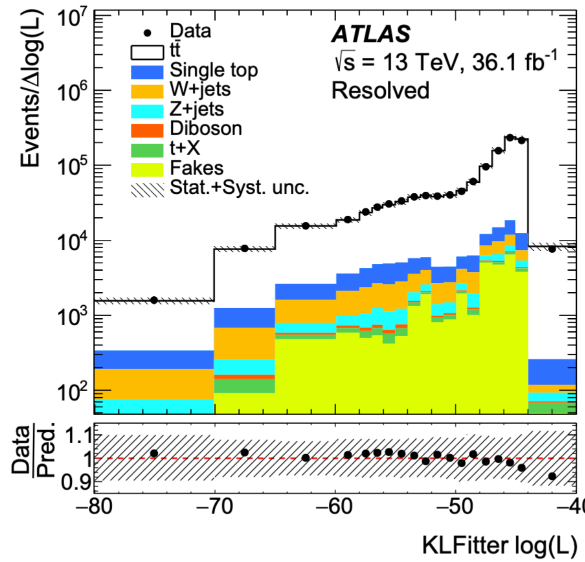
- Extensive program of precision $t\bar{t}$ measurements
  - multiple phase space regions
- Most measurements limited by modelling
- Precise enough to start constraining Standard Model description
- Current simulation provides in general a good description of data
  - Poorer modelling in some kinematic regions (e.g. high p_T)
  - Provides handles for further simulation improvement
- Results are mostly consistent throughout measurements

Backup

[Eur. Phys. J. C 80 (2020) 1092]
[JHEP 01 (2021) 033]
[Phys. Rev. D 98 (2018) 012003]

$t\bar{t}$ reconstruction

- ℓ+jets:
  - 'pseudo-top' algorithm, exploits constraints on W mass and angular separation between jets
  - Kinematic likelihood fit (KLFitter)
    - Only for total phase space cross section in the resolved channel
    - Better resolution for parton-level measurement



- All-hadronic, resolved
  - Set of jets most compatible with $t\bar{t}$ decay chosen through χ^2 discriminant

$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{2\sigma_t^2} + \frac{(m_{j_1 j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3 j_4} - m_W)^2}{\sigma_W^2},$$

- All-hadronic, boosted
  - Two large-R jets, must satisfy 'top-tagging' criteria based on jet mass and substructure